AIRBORNE ROTARY AIR SEPARATOR STUDY

Phase II and III Interim Report

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ABSTRACT

Several air breathing propulsion concepts for future earth-to-orbit transport vehicles utilize air collection and enrichment, and subsequent storage of liquid oxygen for later use in the vehicle mission. Work performed during the 1960's established the feasibility of substantially reducing weight and volume of a distillation type air separator system by operating the distillation elements in high "g" fields obtained by rotating the separator assembly.

This contract studied the capacity test and hydraulic behavior of a novel structured or ordered distillation packing in a rotating device using air and water. Pressure drop and flood points were measured for different air and water flow rates in gravitational fields of up to 700 g. Behavior of the packing follows the correlations previously derived from tests at normal gravity. The novel ordered packing can take the place of trays in a rotating air separation column with the promise of substantial reduction in pressure drop, volume, and system weight. The resutls obtained in the program are used to predict design and performance of rotary separators for air collection and enrichment systems of interest for past and present concepts of air breathing propulsion (single or two-stage to orbit) systems.

I. INTRODUCTION

This report covers the work done by UCIG, Linde Division on NASA Contract NAS3-25560 during the period of 2/88 - 3/90. It essentially deals with the evaluation of "structured packing" for use in the on-board rotary air separator column as an improved mass transfer device. A special test-apparatu was built to evaluate the critical packing surface using air/water fluid combination. Several concepts for air breathing propulsion systems (ACES) for future single stage to orbit launch vehicles require oxygen enrichment of air and subsequent storage of liquefied, enriched air for use as an oxidizer in rocket engines later during the vehicle mission. Thereby, the need for having liquid oxygen on board during takeoff is eliminated. Work performed at Linde during the 1960's showed that fractional distillation of air constitutes a feasible and attractive method for obtaining a low weight and volume enrichment system. The work culminated in the construction and operation of a representative 1/20th scale boilerplate separator which demonstrated functional feasibility and capability of the concept to achieve high throughput at required efficiencies.

In fractional distillation, compressed air bled from the engine at M2.5 to M6 is cooled to saturation conditions and brought into countercurrent contact with a liquid reflux stream in distillation columns where the more volatile nitrogen is concentrated in the vapor phase and oxygen in the liquid phase. The refrigeration required is provided by the liquid hydrogen fuel. It was demonstrated that the weight and volume of the air distillation system could be lowered substantially by operating the system in a high gravitational field generated by rotating the complete separation apparatus. This general concept was first suggested by General Dynamics in the late 1950's and later refined and demonstrated by Union Carbide Industrial Gases, Linde Division (Ref. 1 and 2).

Earlier efforts by Linde (Ref. 3) involved reviewing the results of 1960's work, reporting the results of the studies, and examining the potential impact of the advancements made during the last 21 years. This was documented and presented to the Air Force personnel in February 1988. It clearly indicated that the concept of compact rotating distillation air separators was feasible and that volume and weight, which were compatible or even better than the 1960's aerospace vehicle requirements could be achieved. Our study of the impact of the new technologies has shown that the advances have the potential to make the process more efficient, provide lower pressure drops, simplify the device mechanically and lead to substantial weight and volume reduction. Of the different components and subsystems, the study indicated that the biggest impact on the system weight and volume should come through the use of structured packing Figure 1 in place of the conventional sieve trays in the rotating distillation column, Figure 2. In addition, the study has shown the potential for substantial flexibility in the selection of operating conditions and the possibility for respectable performance at turndown conditions with the use of structured packing, Figure 3. This should allow air collection and enrichment over a broader operating range of the vehicle, Figure 4 and thus help further reduce the air separator and liquefier size and weight.

It is the purpose of this paper to review the results of the current analytical as well as the experimental work at Linde on evaluating the performance of structured packings. This paper describes the apparatus for testing structured packing in a rotating mode, presents a method for predicting the packing performance and analyzes the results with respect to the design of rotary separators for air breathing propulsion (single or two-stage to orbit) systems.

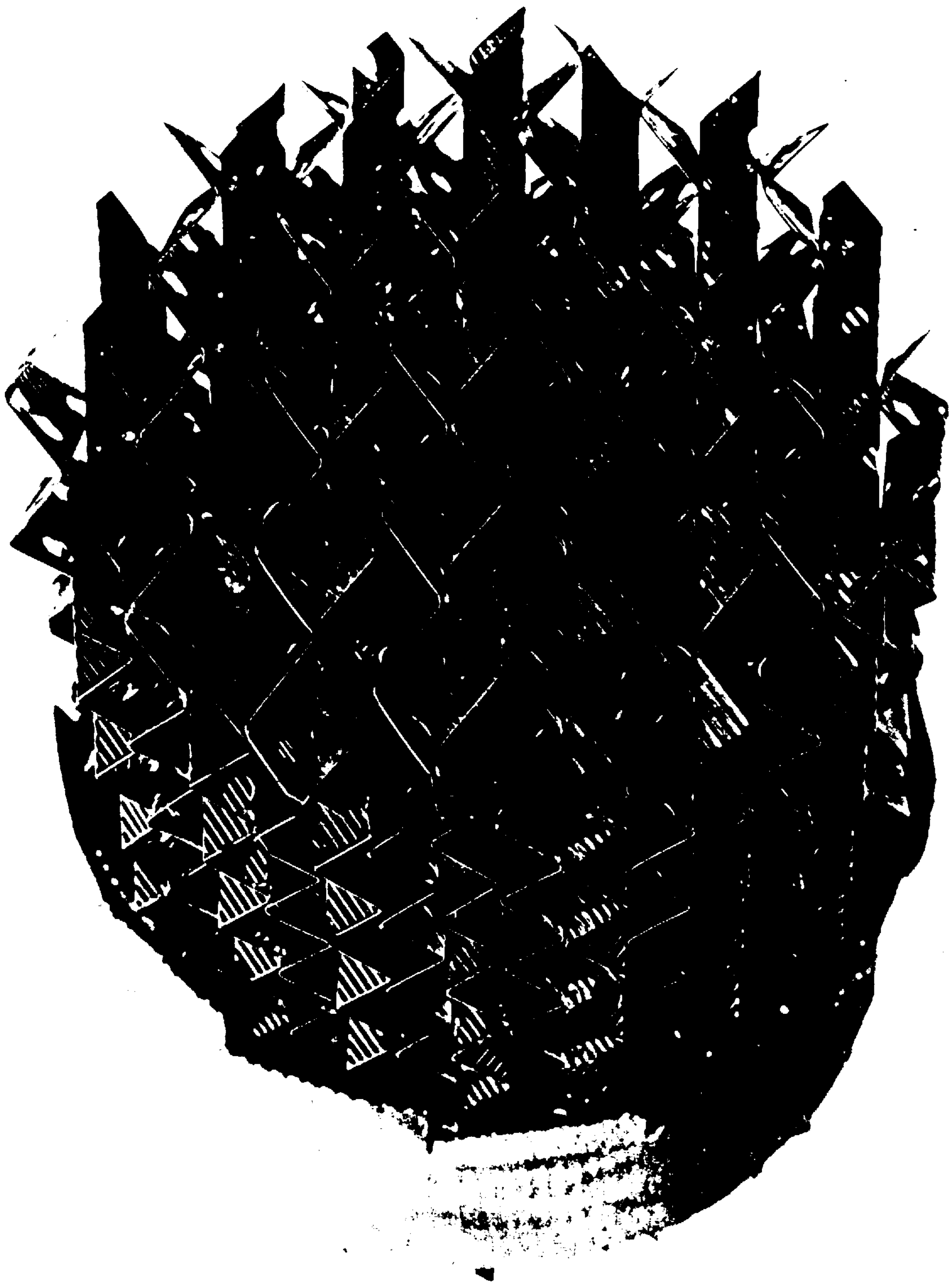


FIGURE 1
STRUCTURED PACKING

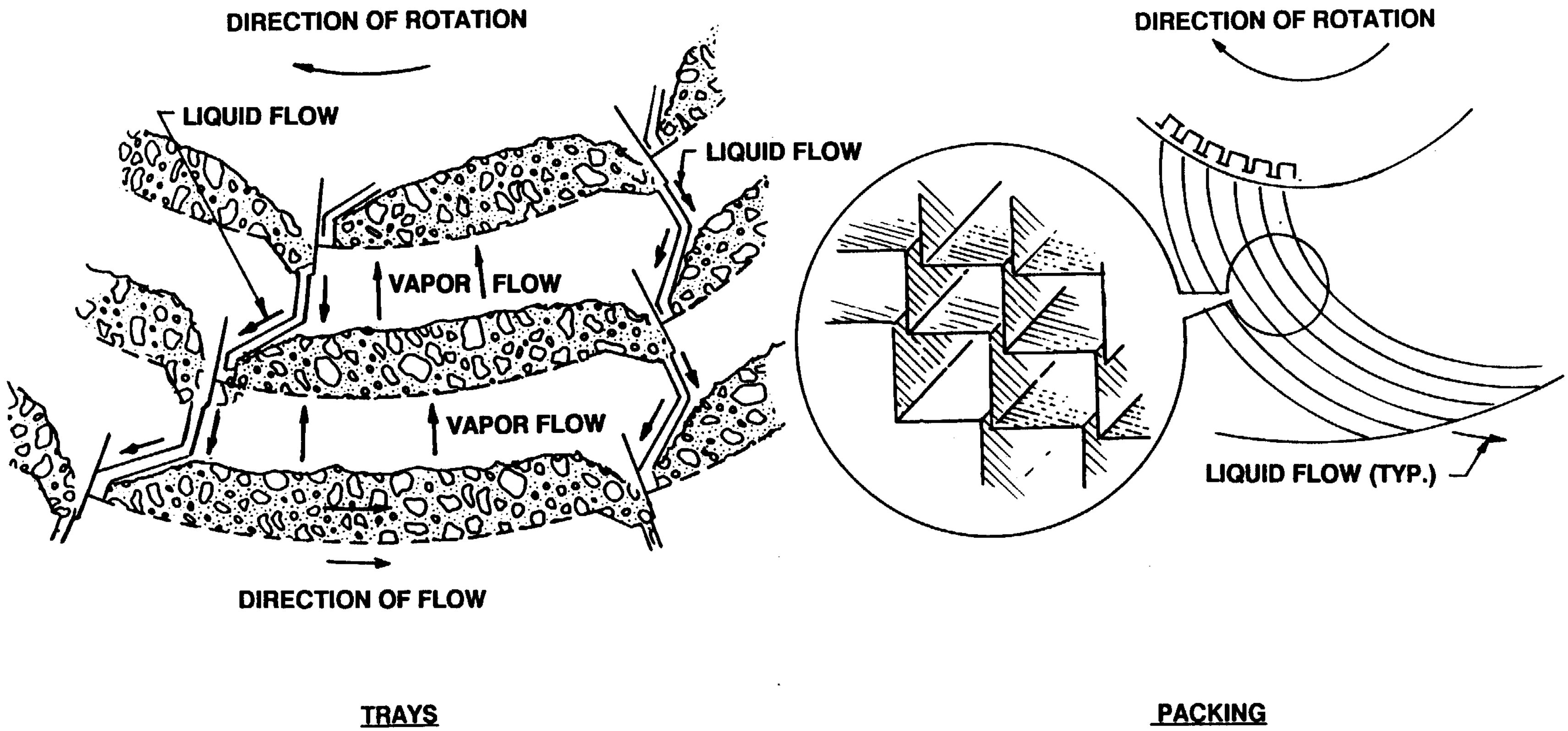


FIGURE 2
ROTATING COLUMN

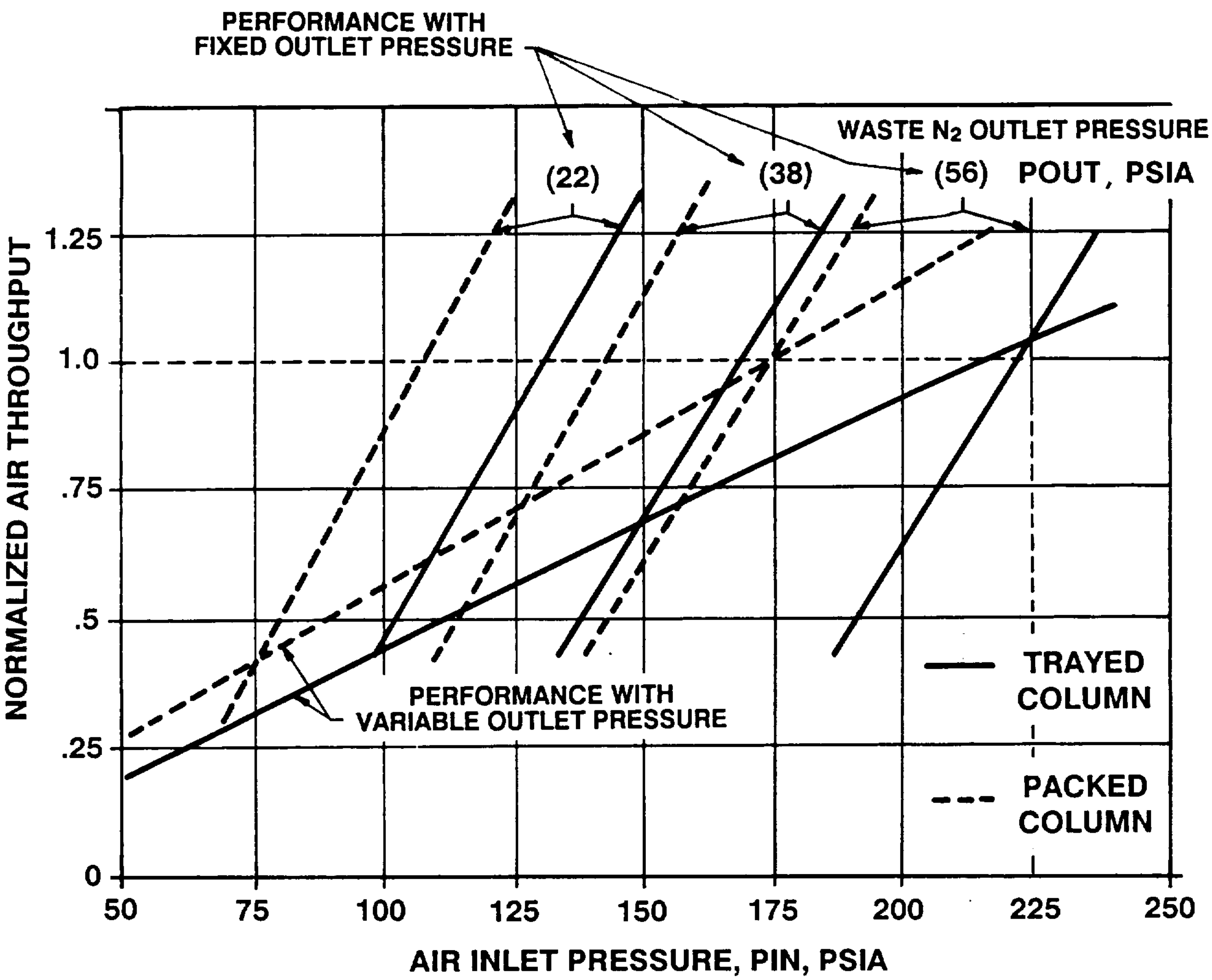


FIGURE 3
AIR SEPARATOR SYSTEM TURNDOWN
PERFORMANCE PROJECTION

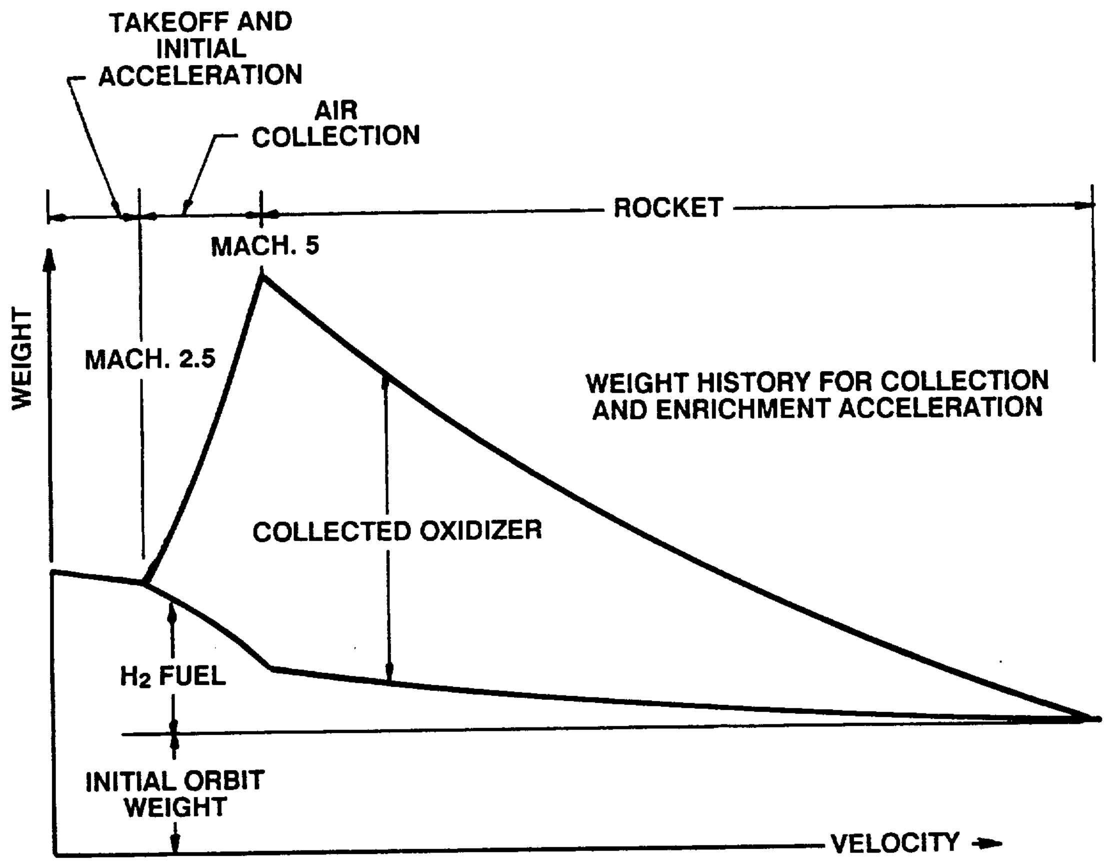


FIGURE 4
TYPICAL CHARACTERISTICS OF ACES SYSTEM

II. BACKGROUND

Basic Distillation

The following section will give a brief overview of the basic distillation process. Distillation is the physical process for the separation of fluid mixtures which is based on the differences in the boiling points of the components. For oxygen and nitrogen at 1 atm the boiling points are 90.2°K and 77.4°K respectively. The different boiling points are one point on the vapor pressure curve of each pure component. The vapor pressure is defined as the pressure at which a pure liquid and its vapor can coexist in equilibrium at a particular temperature. For a fluid mixture, such as liquid air, in equilibrium with vapor, the composition in the liquid phase is different than the composition of the gas phase due to the differing boiling points and the vapor pressure curves of its components. The process of distillation depends on the this property. On a tray, as in Figure 2, the vapor which leaves the liquid on that tray will be enriched in the more volatile or lower boiling point component, in our case N_2; while the liquid that condenses from the vapor phase will be enriched in the less volatile or higher boiling point component, in this case O_2. As this process is repeated on each tray O_2 is concentrated in the liquid phase. In a packed column the vapor/liquid contact occurs in a continuous manner over the height of the packing and the mass transfer is enhanced by the special design of the structured packing, Figures 1 and 2.

Basic Description ACES Systems

Figure 5 shows the basic ACES system using a double column distillation column (Ref. 4). Compressed air bled from the engines is cooled to saturation conditions in a number of heat exchangers against waste nitrogen and hydrogen. Saturated air cleaned of contaminants that would solidify at low temperature is introduced to the bottom of the high pressure column. As the feed air rises

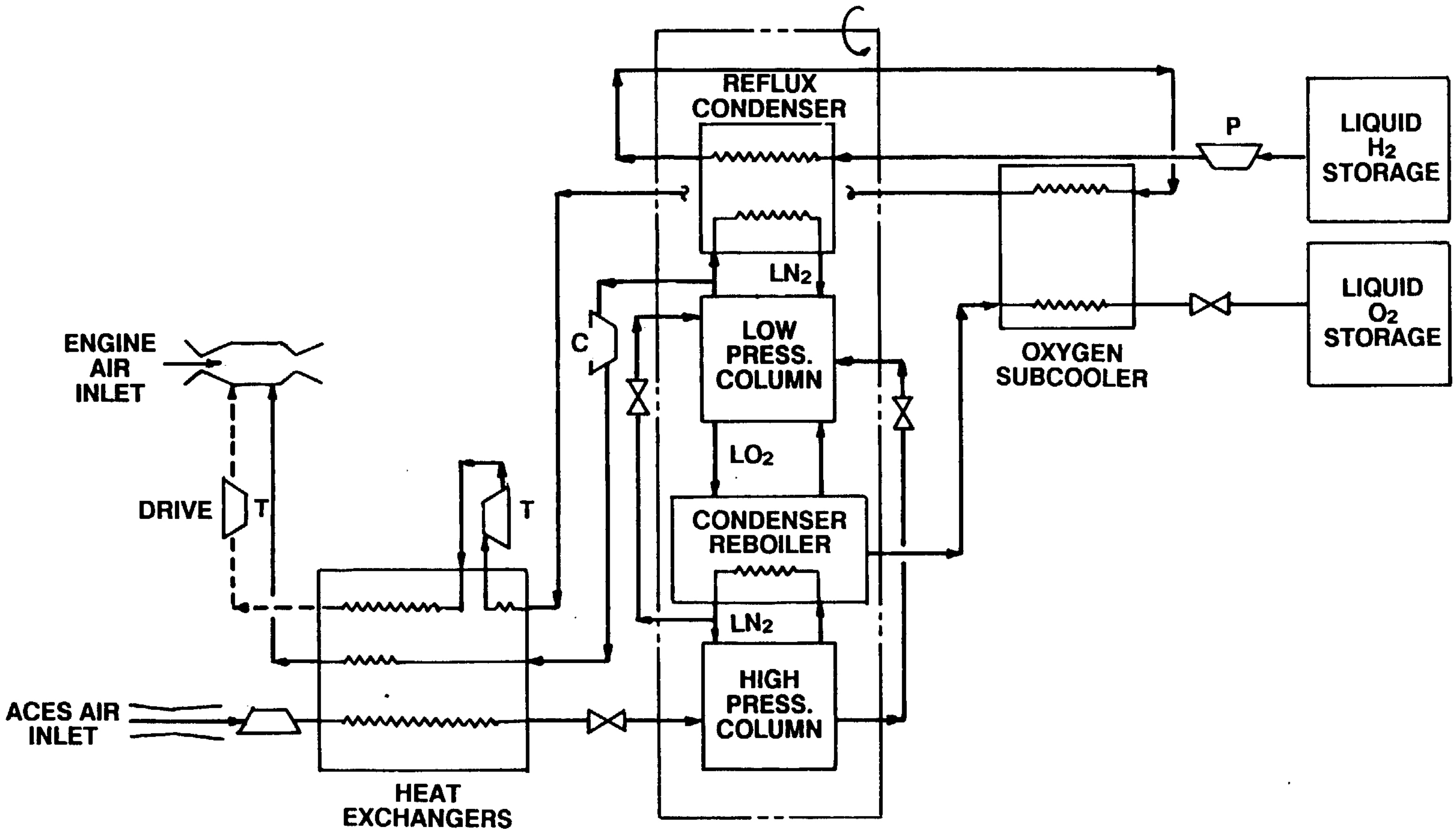


FIGURE 5
AIR COLLECTION AND ENRICHMENT SYSTEM (ACES)
DOUBLE COLUMN DISTILLATION

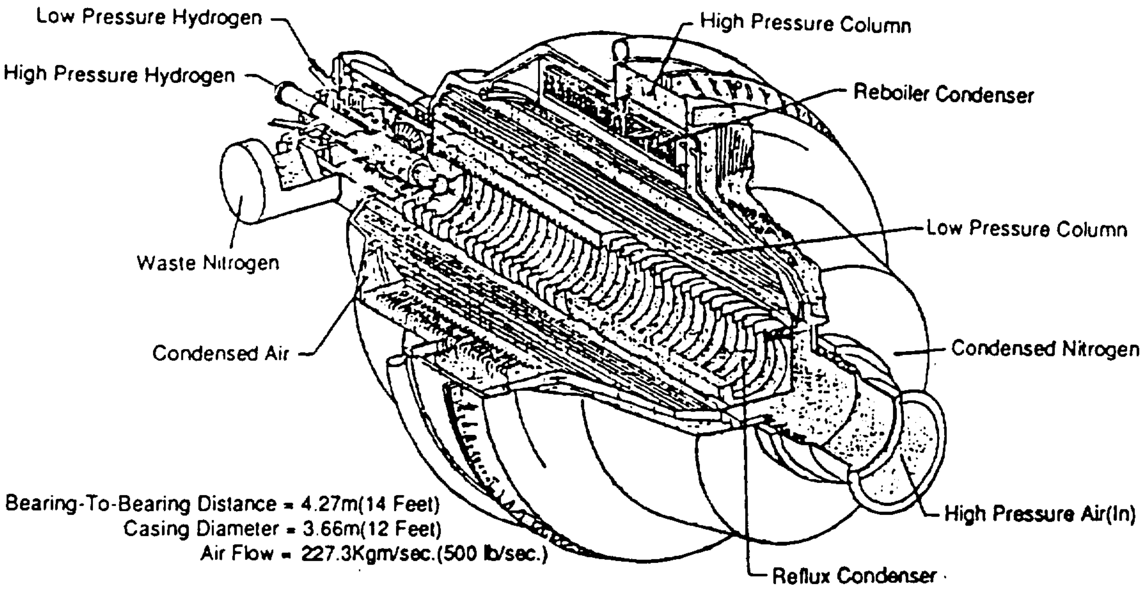
through a series of trays it interacts with down-flowing liquid reflux; the rising vapor increases in nitrogen concentration whereas the falling liquid increases in oxygen concentration. At the top of the column, the nitrogen enriched vapor is condensed in the reboiler condenser unit against boiling oxygen-rich liquid available from the low pressure column. The condensed liquid is split into two portions with one portion introduced as reflux liquid for the high pressure column and another portion which is transferred to the top of the low pressure column. The oxygen enriched liquid at the bottom of the high pressure column is transferred into the midsection of the low pressure column, and serves as liquid feed for the low pressure column. At the top of the low pressure column, the rising nitrogen enriched vapor is split into the two portions; one portion is removed as the waste nitrogen stream, the other portion is introduced into the reflux condenser and liquefied against the hydrogen refrigerant to form additional liquid reflux for the top of the low pressure column. The combined liquid reflux, available from the reflux condenser and transferred from the high pressure column, flow downward through the low pressure column against the rising vapor. At the bottom of the low pressure column the oxygen enriched liquid is boiled in the reboiler condenser against the condensing nitrogen enriched vapor from the high pressure column to produce vapor boilup for the bottom of the low pressure column. A portion of the downwardly flowing oxygen enriched liquid is removed from the reboiler condenser as an oxygen product stream. It should be noted that the refrigeration requirement associated with the reflux condenser at the top of the low pressure column is primarily that associated with the refrigeration required to condense the oxygen stream so that it can be withdrawn as a liquid stream and stored in tanks.

The liquid oxygen withdrawn from the system is cooled further in the oxygen subcooler to the saturation temperature corresponding to storage tank pressure. The waste nitrogen stream is compressed to above the combustion chamber pressure, its refrigeration recovered in the heat exchangers, and reintroduced into the engines. Refrigeration for the processes is provided by the sensible and latent heats of liquid hydrogen supplemented by additional refrigeration produced at appropriate levels by hydrogen expansion and recovery of the heat of ortho-para hydrogen conversion.

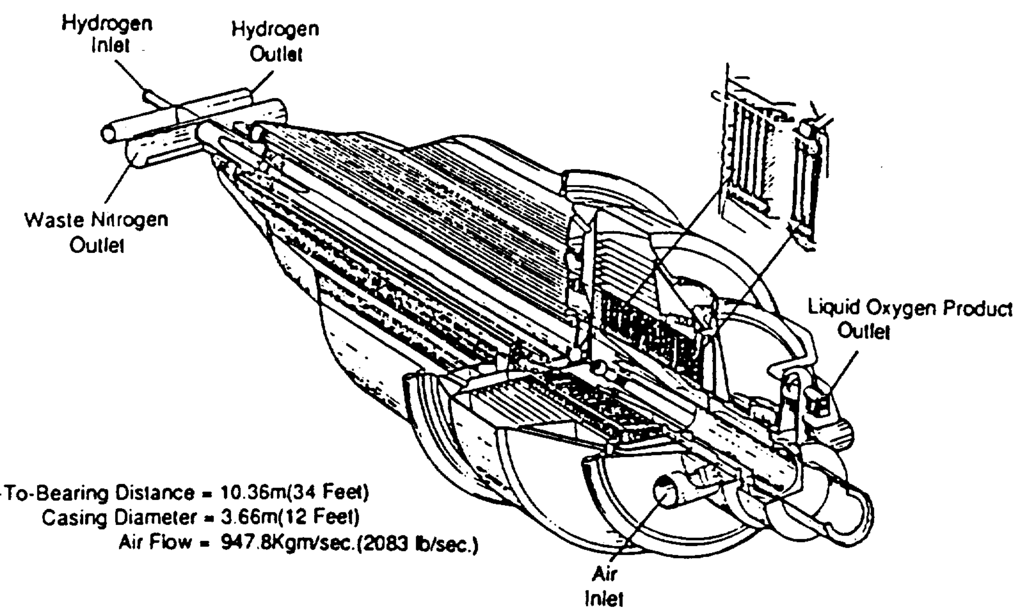
This discussion will be limited to the distillation separator proper, since it provides the greatest departure from conventional technology. The above double column air separation process has been very effective in commercial practice from the standpoint of good product recovery with efficient use of refrigeration. These two attributes also resulted in the selection of this process from several alternatives studied for the ACES system.

In the rotating distillation column the fundamental arrangement is essentially identical to the commercial two-column reboiler-condenser except that the assembly is rotated. On the rotating device, vapor is introduced at the outer diameter and withdrawn at the inner while liquid flows radially outward. An artist's concepts of the full scale airborne separators utilizing tray technology for processing 227.3 Kgm/sec (500 lbs/sec) and 946.8 Kgm/sec (2083 lb/sec) of air is shown in Figure 6. The latter has the components arranged side by side to limit the outer diameter.

The reason that mass transfer elements, depicted by sieve trays in Figure 7, can be reduced in volume is the high gravitational field which permits high vapor velocity before entrainment of liquid droplets occurs and reduces the foam height of the aerated liquid flowing across the trays. Surprisingly, mass transfer efficiencies are high in spite of short contact time between vapor and liquid. On the negative side, pressure drop required to support the hydrostatic head is increased. The throughput volume improvements possible for sieve trays at high "g" are summarized in Figure 8. Here N_g is defined as $R\omega^2/g$.

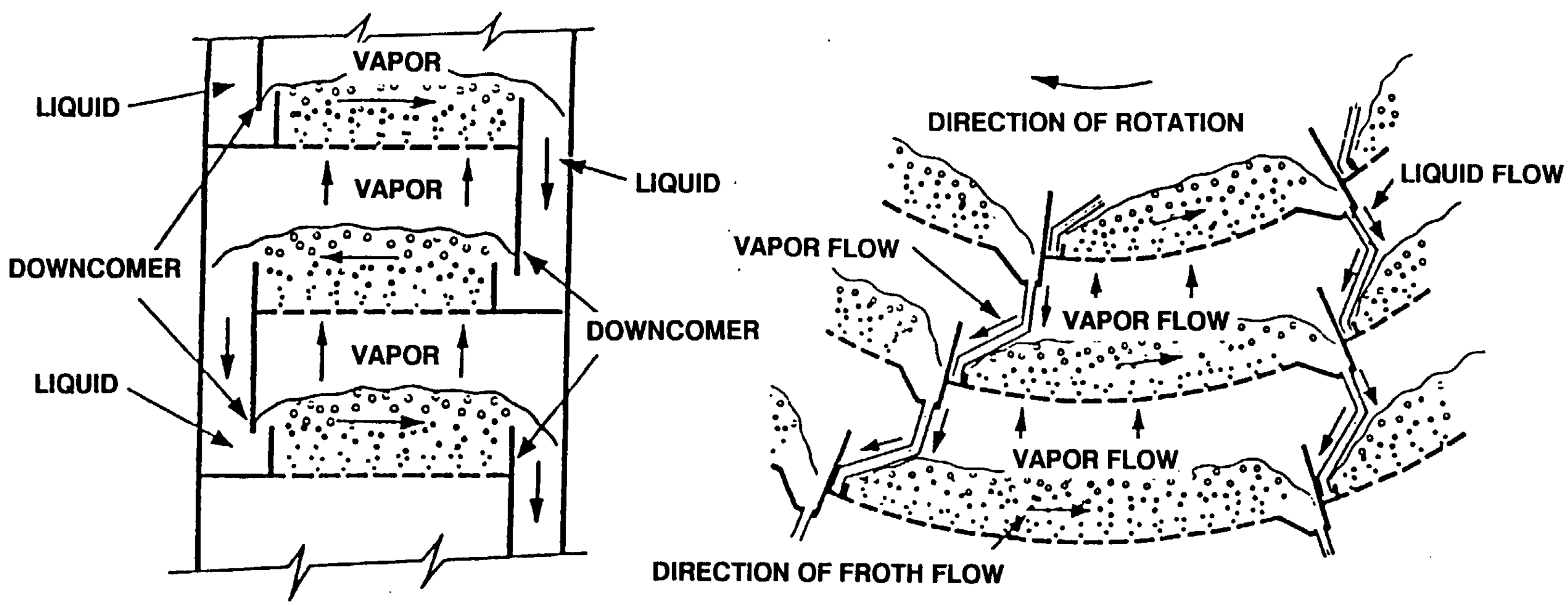


a) REVERSIBLE ORBITAL LAUNCH SYSTEM



b) AIR COLLECTION AND ENRICHMENT SYSTEM (ACES)

FIGURE 6
ROTATING AIR SEPARATORS



a) STATIONARY TRAYS

b) ROTATING TRAYS

FIGURE 7
DISTILLATION TRAYS

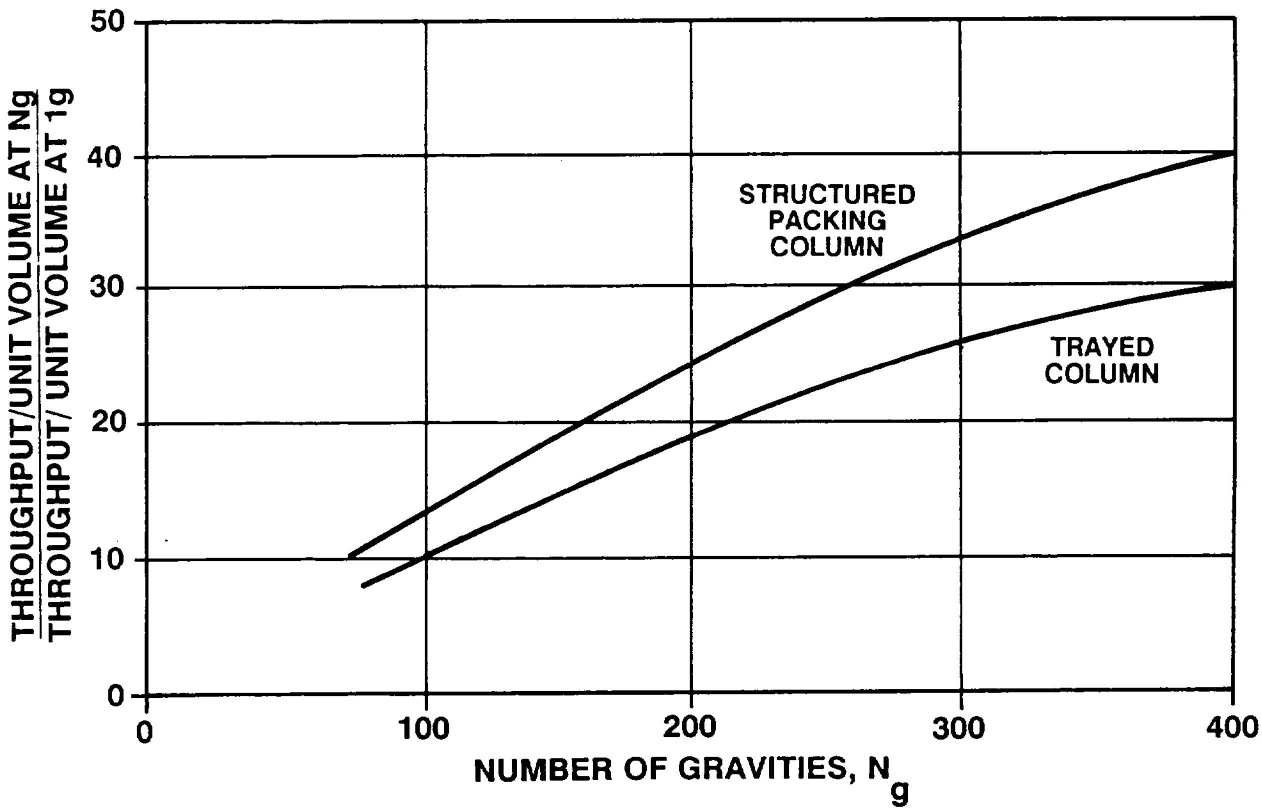


FIGURE 8
HIGH G DISTILLATION PERFORMANCE COMPARISON

The general dimensions and weights of a separator designed during the 1960's on the basis of the tray technology is shown in Figure 6, for an air separator with an air throughput of 946.8 Kgm/sec (2083 lb/sec) producing 90% O_2 liquid at 90% recovery was 4454.5 Kgm (9800 lbs) at a separator air inlet pressure of 1552.5 kPa (225 psia) and waste N_2 outlet pressure of 386.4 kPa (56 psia). This was within the target of 5 Kgm of separator per Kgm/sec of air flow, (5 lbs per lb/sec).

Use of structured packing instead of the conventional sieve trays in the rotary air separator columns is considered to be the key technology advancement with a large impact on the weight, volume and mechanical simplicity of the separator column. Its use should be able to reduce the separator weight and volume, Figure 9 and Table I, or even more importantly allow air separation at lower inlet pressures, Figure 3, and thus increase the range over which the air could be collected and enriched. This in turn, could help reduce the weight and volume of the entire vehicle. The basis for the weight comparison for the aluminum trayed and packed column is given in Table II.

III. STRUCTURED PACKING

The most significant opportunity for the system's size reduction appears to be presented by the use of packing, specifically structured packing in place of trays. Structured packing provides a significant amount of surface area typically in the form of corrugated sheet metal (Figures 1 and 2) along which liquid is brought into continuous countercurrent contact with vapor as in a wetted wall column. Flow of liquid and vapor are essentially vertical or radial on a rotating device. At 1 "g" the advantage of packing over trays lies in a substantially reduced pressure drop at somewhat improved throughput. Since in the rotating trayed column, the rotational speed and throughput per unit volume was limited by pressure drop, the low inherent pressure drop of packing permits a higher rotational speed and therefore

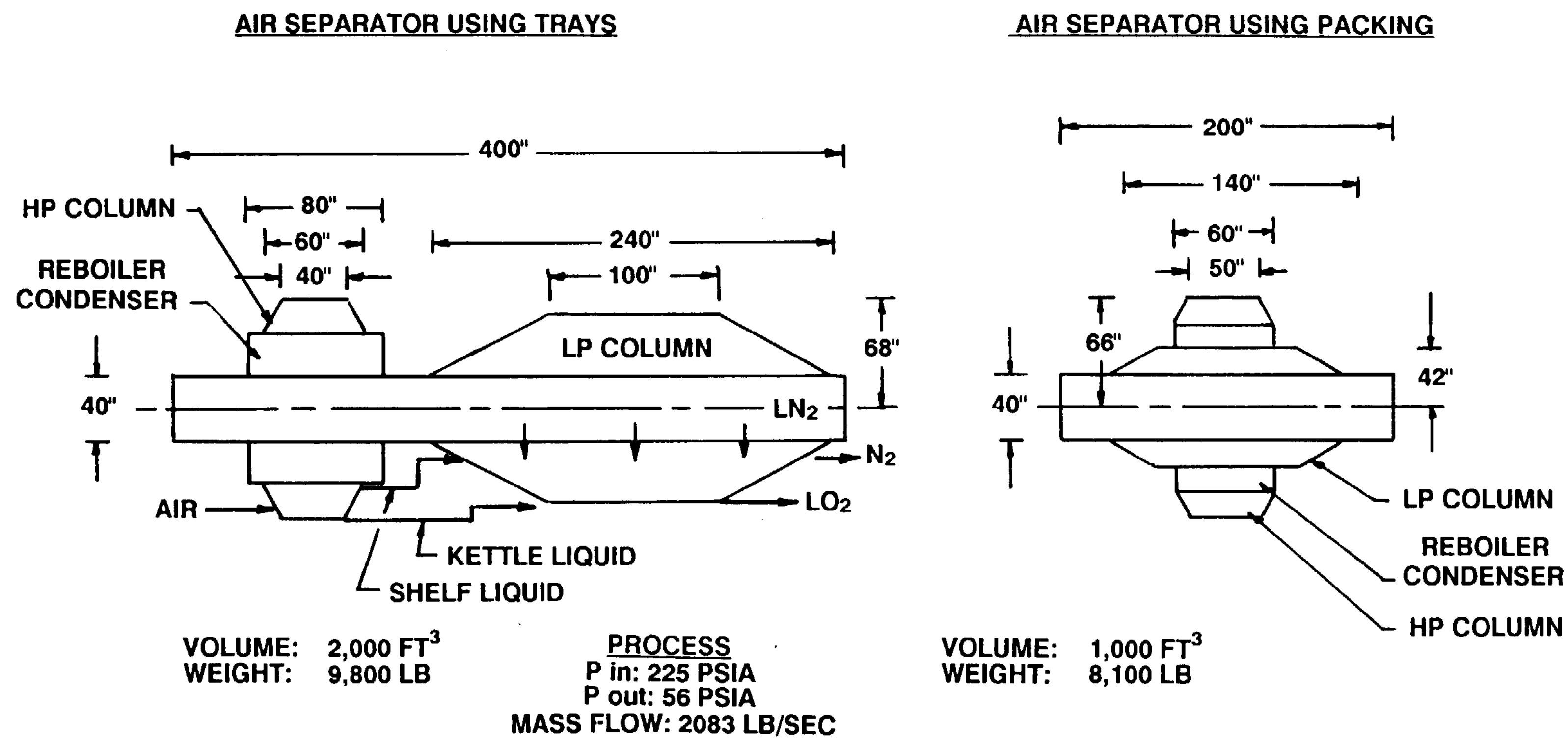


FIGURE 9
ROTARY AIR SEPARATOR CONFIGURATIONS

Table I

System Weight Summary

Air Separator Column Internal	Trays		Structured Packing		
Column Configuration	Side-by-Side		Stacked		
Column Inlet Air Pressure, KPa (psia)	1552.5 (225)	1552.5 (225)	1552.5 (225)	1552.5 (225)	1207.5 (175)
Column Outlet N_2 Pressure, KPa (psia)	386.4 (56)	386.4 (56)	386.4 (56)	386.4 (56)	386.4 (56)
Weight Projection Period	1960's	1989	1989	1989	1989
Material of Construction	Al	LiAl	Al	LiAl	LiAl
Air Separator System Weight, (KCMS) (Lbs)	4454.5 (9800)	3227.3 (7100)	3682.0 (8100)	2954.5 (6500)	3454.5 (7600)

Table II - Separator Weight Details

Item	Trayed Column (Figure 9) Description	Trayed Column Total Weight, Lbs	Structured Packing Column (Figure 9) Description	Structured Packing Column Total Weight, Lbs
Rotation	45 Rad/Sec		60 Rad/Sec	
Reboiler/Condenser	13,000 ft^2, Shell .071" Al Tube Wall .013", Side Wall .4" ID 48", OD 84", L=80",U=3,000 BTU/Hrft^{2o}F	3,450	9,000 ft^2, Shell .071" Al Tube Wall .013", Side Wall .4" ID 84", OD 104", L=60", U=4300 BTU/Hrft^{2o}F	2,000
Shaft	40" O.D. x 400" x .3" Wall, Al	1,440	40" O.D. x 200" x .3" Wall, Al	720
High Pressure Column	10 Trays, .035" Thick, Al 564 ft^2 Total Tray Area Shell .56", Ends .024" ID 84", OD 144", L=60"	1,390	.002" Al 1000 ft^2/ft^3, 14 lb/ft^3 ID 104", OD 132", L=60" Shell .56" Thick, Ends .024"	1,950
Low Pressure Column	16 Trays, .010" Thick Al 145 ft^2 Total Tray Area Shell .15", Ends .013" ID 48", OD 60", L=240"	820	.002" Al, 1000 ft^2/ft^3, 14 lb/ft^3 ID 48", OD 84", L=140" Shell .15", Ends .013"	1,530
Piping		870		500
Diffusers		600		450
Separation Chamber		500		300
Bearings and Support		380		250
Turbine		150		150
Drive		150		150
Kettle Separator		100		100
	Total	9,850	Total	8,100

significantly greater throughput while still achieving reduced pressure drops. The higher rotational speeds have the side benefit of also achieving higher heat transfer coefficients in the reboiler condenser. Structured packing has seen significant commercial advances over the past few years in 1 g applications. A variation in random packing has been used in a high "g" rotating device by ICI to achieve improved throughput and small radial heights per transfer unit. For the ACES application, structured packing is preferred since it has low pressure drop and its more ordered geometry provides for higher throughput, as well as easier installation in a rotating pressure vessel. An estimate was prepared of distillation performance by extrapolating 1 "g" correlations for the case at hand using a high density packing (3281 m^2/m^3, 1000 ft^2/ft^3) made from 7.8 x 10^{-5} mm (0.002") thick aluminum foil, Figures 10 and 11. It should be noted that since significant extrapolations from 1 "g" behavior was required, experimental confirmation of predictions by tests in a rotating device was carried out.

Figure 9 summarizes the projected results for the packing. It can be seen that weight savings of 17% are possible at constant pressures. The reduced column heights with packing also permit going from a side by side arrangement to a simpler stacked arrangement of separator components for large throughputs. Alternately the packing permits a 345 kPa (50 psi) reduction in separator air inlet pressure. For the system studied by Rockwell International, lowering of the inlet pressure resulted in favorable tradeoffs in overall vehicle payload.

IV. ROTATING COLUMN TEST APPARATUS

In order to evaluate the performance of the structured packing at different "g"s, a rotating column test apparatus was built as shown schematically in Figure 12. Its scaled version is shown in Figure 13 and the spray nozzle arrangement is shown in Figure 14. As shown in Figure 12, the test of the packing had 2.5"

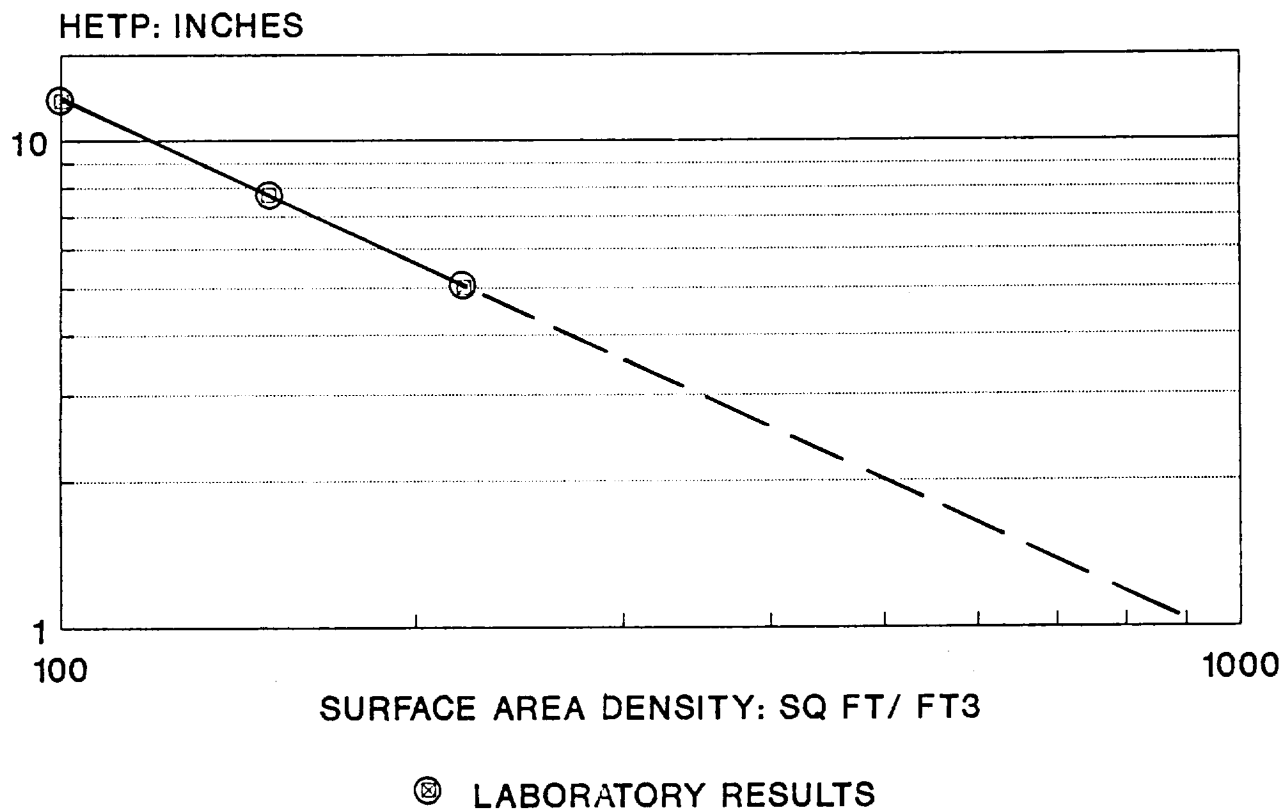


FIGURE 10
STRUCTURED PERFORMANCE,EFFECT OF SURFACE AREA ON HETP

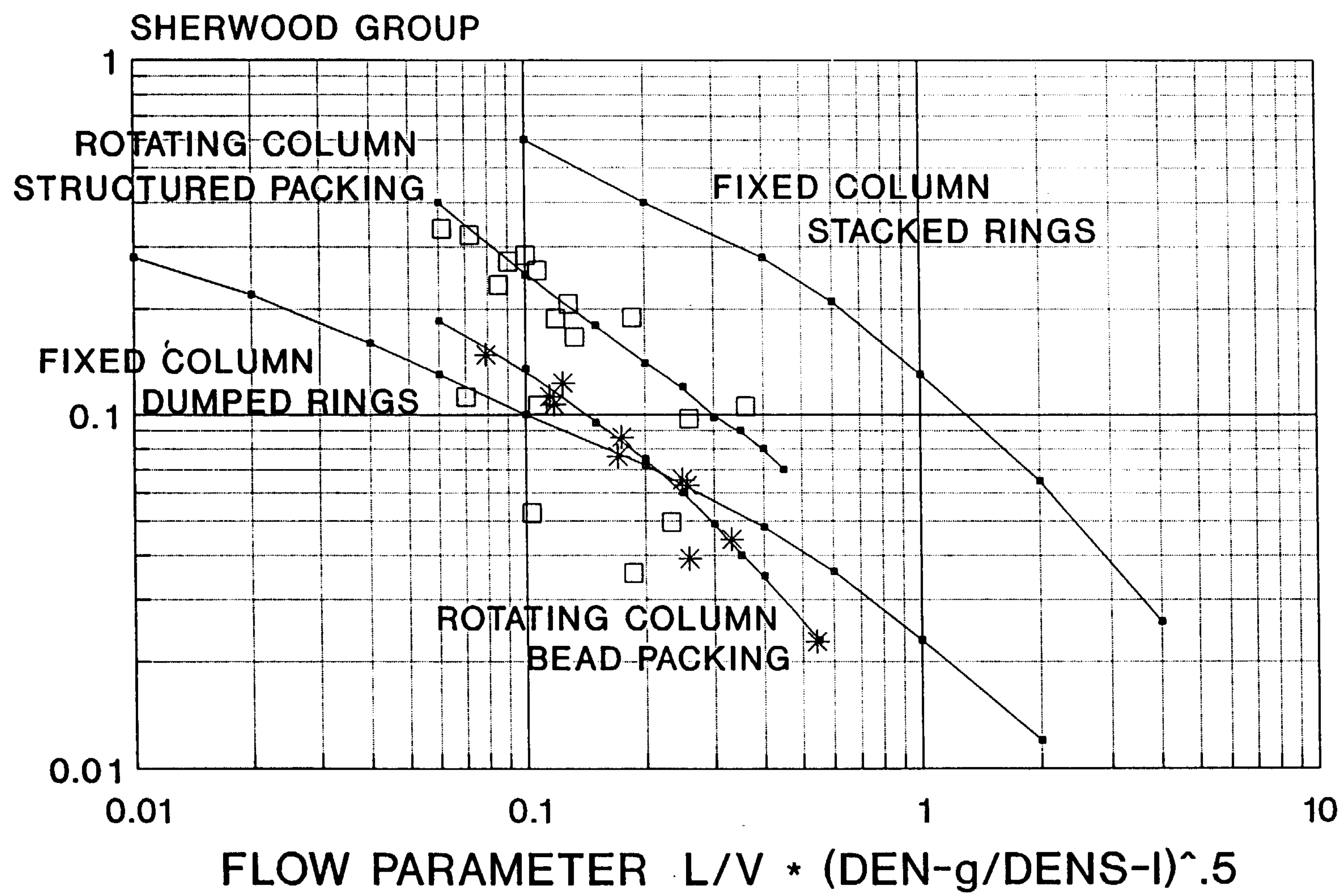


FIGURE 11
SHERWOOD CORRELATION COMPARISON, ROTATING AND SHERWOOD FIXED COLUMN DATA

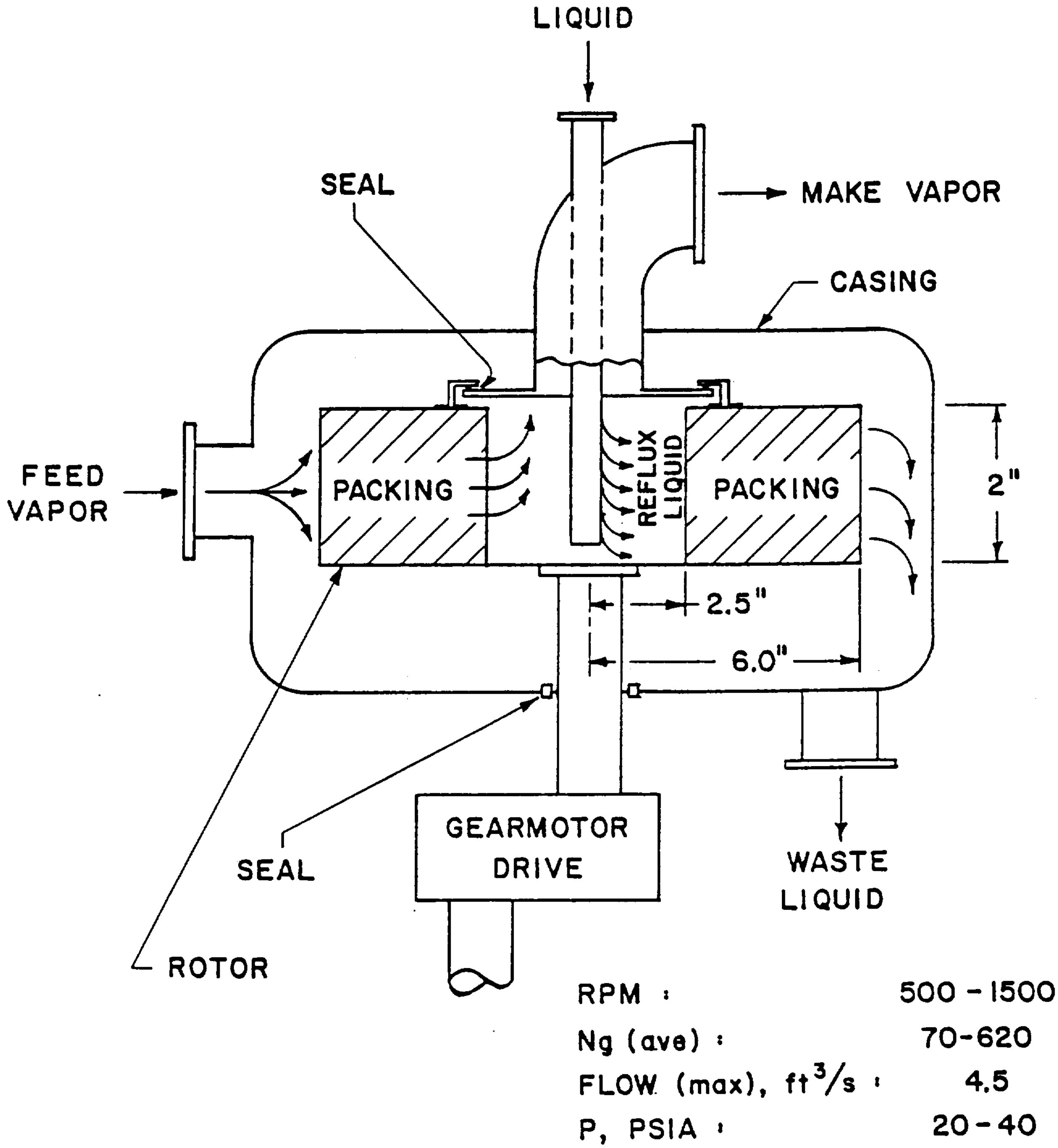


FIGURE 12
ROTARY AIR SEPARATOR

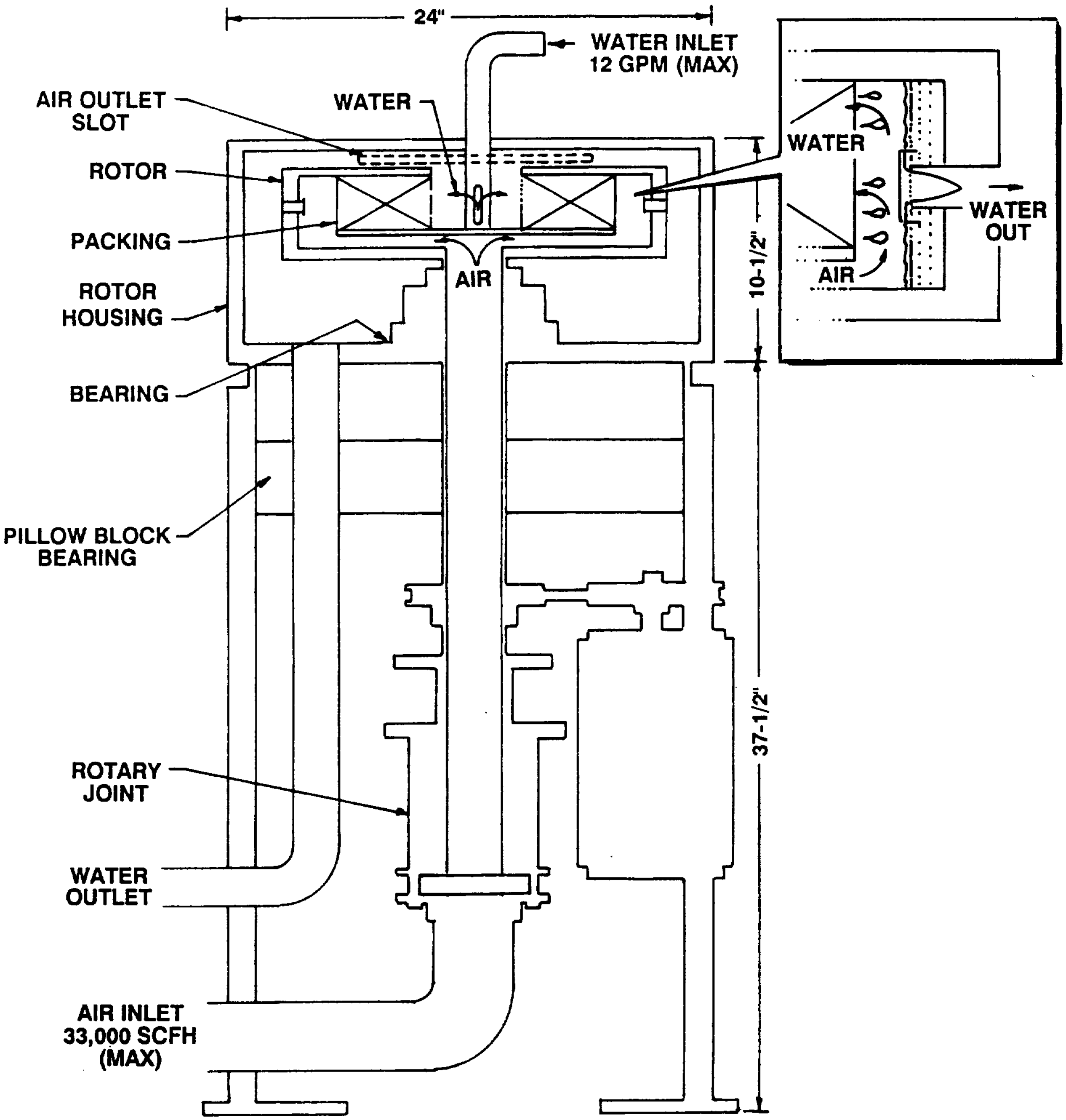


FIGURE 13
AIR-WATER TEST UNIT, MAJOR COMPONENTS

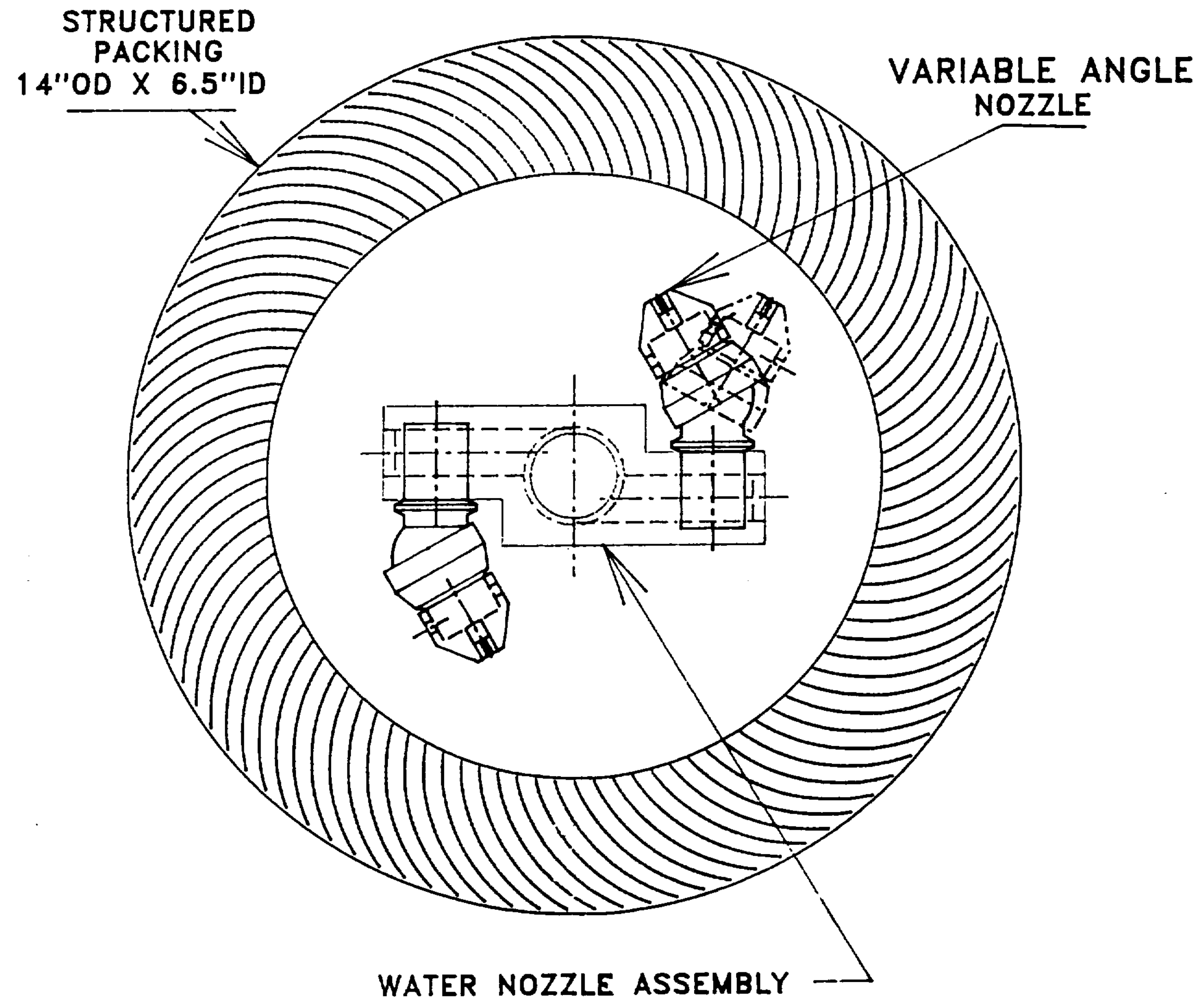


FIGURE 14
TOP VIEW, SPRAY NOZZLE AND PACKING

inner radius and 7.0" outer radius with the packing height of 2.0". A picture of the installed structured packing is shown in Figure 15. Its helical contour was engineered to provide a constant flow cross section through each flow passage. The test packing could be rotated between 500 and 1500 RPM with "g" loads ranging from 70 to 700. As shown in Table III, the packing was evaluated using the air/water fluid combination to determine its flooding characteristics at different "g" loads. The water flow, ranging up to 12 gpm, was distributed at the inner radius of the packing using a special nozzle while the air flow, up to 550 SCFM, was introduced at the outer radius of the packing through a special rotary joint. A transparent plastic cover was used at the top of the packing to observe the flooding condition at the packing's inner radius. It should be noted that the flooding condition occurs when the water flow is impeded by the momentum of the air flow at a given "g" level, such as to cause water holdup and frothing at the packing's inner radius.

The tests consisted of operating the column at different RPM, air and water flow rates to determine the envelope of the flooding conditions and pressure drop. A typical test run would involve varying of air flow at a given RPM and water flow rate until the flooding condition is observed. Tests were conducted with two types of packings as shown in Table IV. Randomly dumped packing using glass beads, .12" dia, were tested to determine the low range of the flow capacity while the Linde designed packing was tested to evaluate the improvement over the random packing.

V. ANALYTICAL PREDICTION

Use of a rotating packed bed for enhanced distillation in a compact configuration is a more recent development (Ref. 5). The dramatic size reduction (Ref. 6) is achieved due to very high allowable gas velocities resulting in small flow cross section and due to high mass transfer coefficients resulting in reduced packing height or HETP (Height Equivalent of Theoretical Plate). Dramatic

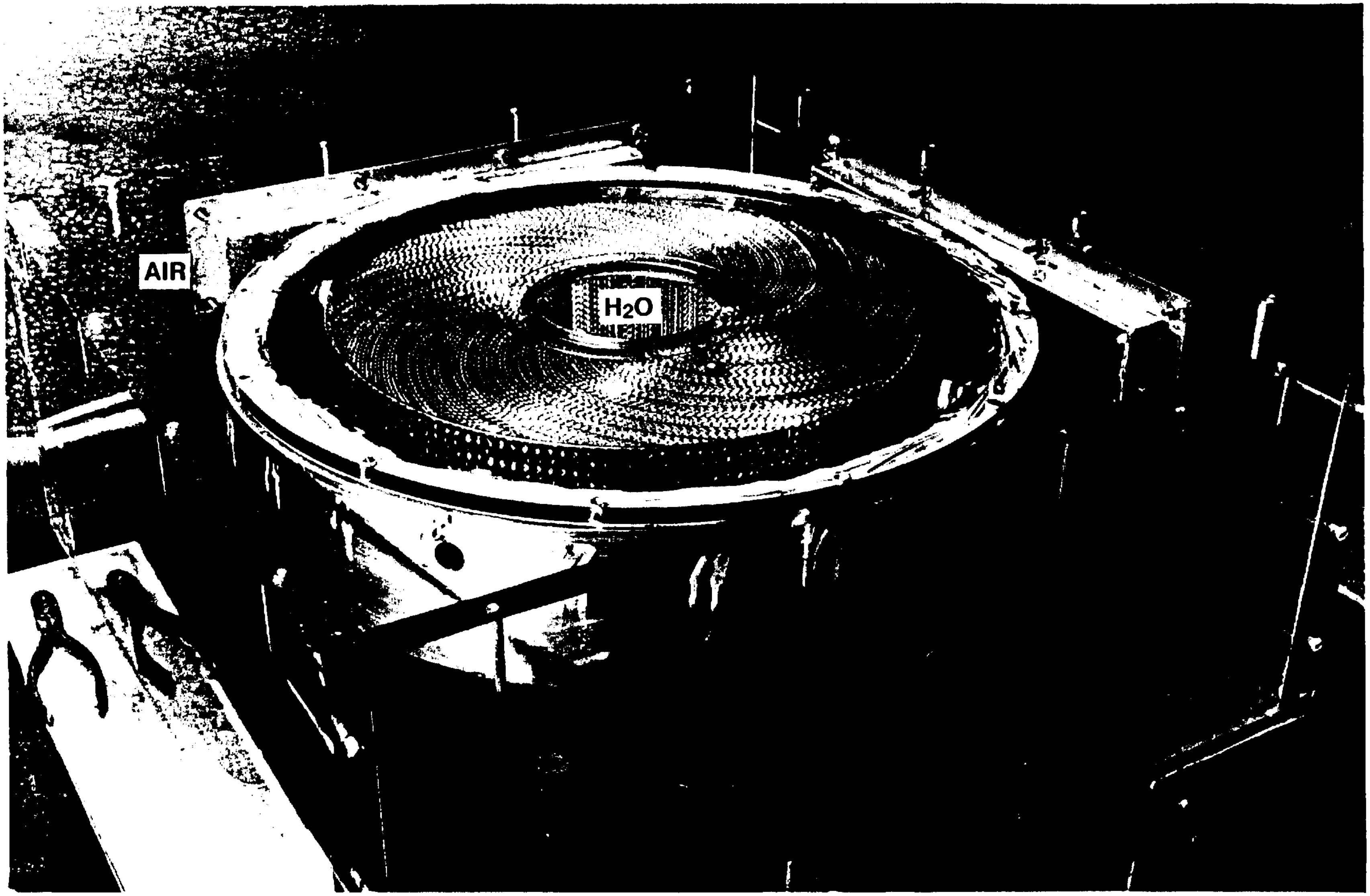


FIGURE 15
ROTATING PACKED COLUMN

Table III

Rotating Column Air/Water Test Apparatus

Test Conditions

Rotor Speed:	1500 RPM	
Air Flow:	20,000 SCFH	
Water Flow:	8 GPM	
Pressure:	1 ATM	
"g" Level:		
	70g	700g
RPM:	500	1500
RAD/Sec	52	157
I.D. (6.0")	20	180
O.D. (14.0")	50	450

Table IV

Types of Packing

	Beads	Linde Packing
Material	Glass	Aluminum
Shape	Spheres	Corrugated Foil Sheets
Nominal Size		
O.D. (In.)	0.12	
Foil Thickness (In.)		.006
Corrugation		
No./In.		8
Height, In.		.045
Angle		45
Area Density, ft^2/ft^3	360	725
Porosity, ϵ	.43	.82
Strip Height		2.27
Packing		
I.D. (In.)	6.0	6.5
O.D. (In.)	14.0	14.0
Height (In.)	2.31	2.27

size reduction of the air separation column when operated under high "g" condition is depicted in Figure 16.

High allowable gas velocities prior to flooding can be understood by examination of the dimensionless group in the Sherwood flooding correlation (Ref. 7) for the gravity-flow packed bed (Ref. 8), Figure 11. This dimensionless grouping, P_{SH} as shown below, is the ratio of the inertia force of the gas to the gravity force acting on the liquid. In order to achieve a compact device both high gas velocities and high surface areas are required. For a constant bed geometry and Sherwood number higher gas velocities can only be obtained by achieving higher gravitational forces.

$$P_{sh}=\frac{U^2 A_o \rho_g}{g\varepsilon^3 \rho_l}\left[\frac{\mu_l}{\mu_w}\right]^{0.2} \propto \frac{L}{G}\sqrt{\frac{\rho_g}{\rho_l}}$$

In the above group:

g:	gravity acceleration, ft/sec^2
U:	gas superficial velocity, ft/sec
A_o:	specific surface area, ft^2/ft^3
ε:	packing porosity
ρ_g:	gas density, lb/ft$_3$
ρ_l:	liquid density, lb/ft^3
μ_l:	liquid viscosity, lb/hr
μ_w:	water viscosity, lb/hr

In a rotating packed column, the centrifugal force is used as the driving force for liquid flow through the packed bed. Assuming that the Sherwood correlation applies to the rotating bed, the above "g" term should be replaced by the centrifugal acceleration $r\omega^2$ (where r is the bed radius and ω is the rotational speed, rad/sec). The value of ω^2 can be made many times higher than the value of "g" by using high rotational speed and large radii. It can be seen from the above Sherwood group that the superficial velocity, U will increase with the square root of $r\omega^2$. It can also

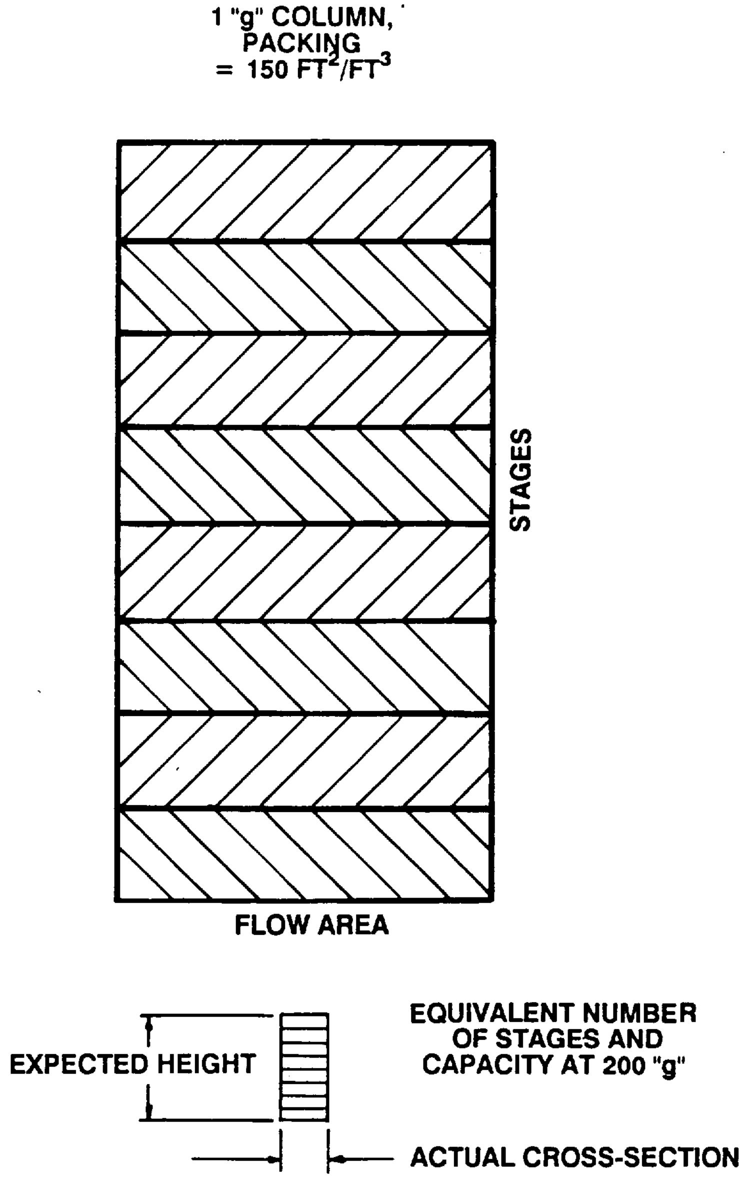


FIGURE 16
SIZE REDUCTION DUE TO ROTATION

be seen that the $r\omega^2$ will have to be further increased to achieve compaction with the use of high area density packing, Figure 1. The advantage of the high porosity possible with the structured packing (Table IV) resulting in high allowable gas velocities is also evidenced in the above dimension group (Ref. 8). The structured packing porosity should result in a factor of almost 7 increase in gas velocity over the glass bead packing based on the Sherwood group.

Using the above correlation, the allowable superficial velocity i.e., the flow capacity of the random beads packing and the structured Linde packing using the air/water fluid combination was determined as shown in Table V. It shows an increased flow capacity by a factor of 2.6 of the Linde packing over the bead packing at a flow parameter of .1, Figure 11 even though the structured packing has almost twice the area density of the beads, Table IV.

VI. EXPERIMENTAL DATA

The following results are based on limited testing of a rotating column using air and water. A total of 28 flooding points were obtained. The test results have shown the structured packing will achieve the capacity goal and even better performance may be achieved by optimizing the spray nozzle. Further cryogenic testing is required to measure the mass transfer of the structured packing which to date have been extrapolated from 1 g test data.

Experimental data on packings using beads as well as the Linde structured packing are shown in Table VI and Figure 17. Significant increase in the air flow capacity with increase in the rotational speed of the test column is apparent from Figure 17. A much higher flow capacity of the Linde designed structured packing over that for the beads is also evident from Figures 11 and 17. The five low flood points for the structured packing were probably caused by incorrect water nozzle angle resulting in early flooding.

Table V

Flow Capacity of Packing Using Air/Water Combination

$$P_{SH}=\frac{U^2 A_o}{R\omega^2 e^3}\left(\frac{\rho_g}{\rho_l}\right)\left(\frac{\mu_l}{\mu_w}\right)^{.2}$$

$$U=\left[\frac{P_{SH} R\omega^2 e^3}{A_o} x \frac{\rho_l}{\rho_g} x \left(\frac{\mu_w}{\mu_l}\right)^{.2}\right]^{1/2}$$

for the test column

R = .25 Ft μ_l = 1 cp
ω = 60 Rad/s μ_w = 1 cp
ρ_g = .072 lb/ft^3 ρ_l = 62.4 lb/ft^3

for the bead packing

A_o = 360 ft^2/ft^3 ϵ = .43 ft^3/ft^3
P_{SH}= .13 at flow (L/G) • $(\rho_g/\rho_l)^{1/2}$ = .1

U_B = 6.8 ft/s

for the structured packing

A_o = 700 ft^2/ft^3 ϵ = .82 ft^3/ft^3
P_{SH}= .25 at flow (L/G) • $(\rho_g/\rho_l)^{1/2}$ = .1

U_S = 17.8 ft/s

under test conditions $\frac{U_S}{U_B}$ = 2.62

This shows that the structured packing has a throughput of 2.6 times that of the bead packing.

Table VI - Rotating Column Flooding Data

Packing Type	RPM	Spray Angle & Rotation	ID Ft	Water Flow		Air Flow			Flow* Parameter	Sherwood Number
				GPM	#/Hr	SCFH	#/Hr	Ft/s		
Structured	317	30° CCW	0.2708	8.04	4018	5161	387	4.45	0.360	0.105
$A=725 ft^2$	460	30° CCW	0.2708	8.04	4018	10039	752	8.66	0.185	0.188
$\epsilon = .82$	460	30° CCW	0.2708	5.42	2709	11697	876	10.09	0.107	0.256
H = 2.27"	460	30° CCW	0.2708	4.10	2048	13132	984	11.33	0.072	0.323
	460	30° CW	0.2708	8.04	4018	7198	539	6.21	0.258	0.097
	460	30° CW	0.2708	5.42	2709	9416	706	8.13	0.133	0.166
	460	30° CW	0.2708	4.10	2048	11174	837	9.64	0.085	0.233
	603	90° CW	0.2500	6.73	3365	12196	914	11.40	0.128	0.206
	603	90° CW	0.2500	5.42	2709	14002	1049	13.09	0.090	0.271
	603	90° CW	0.2500	4.10	2048	15585	1168	14.57	0.061	0.336
	718	90° CW	0.2500	7.39	3692	17010	1275	15.90	0.100	0.283
	718	30° CW	0.2708	8.04	4018	8011	600	6.91	0.232	0.494
	718	30° CW	0.2708	8.04	4018	15585	1168	13.45	0.119	0.187
	1061	30° CCW	0.2708	8.04	4018	17347	1300	14.97	0.107	0.105
	1061	30° CCW	0.2708	5.42	2709	17839	1337	15.40	0.070	0.112
	1061	30° CW	0.2708	8.04	4018	10039	752	8.66	0.185	0.035
	1061	30° CW	0.2708	5.42	2709	12196	914	10.53	0.103	0.052
Beads	603		0.2500	4.10	2048	3700	277	3.40	0.256	0.063
$A=360 ft^2$	603		0.2500	2.76	1381	5161	387	4.74	0.124	0.122
$\epsilon = .43$	1004		0.2500	8.69	4343	3700	277	3.40	0.543	0.022
H=2.31"	1004		0.2500	7.39	3692	5161	387	4.74	0.331	0.044
	1004		0.2500	6.73	3365	6269	470	5.76	0.248	0.065
	1004		0.2500	5.42	2709	7198	539	6.61	0.174	0.086
	1004		0.2500	4.10	2048	8011	600	7.36	0.118	0.106
	1491		0.2500	8.04	4018	7198	539	6.61	0.258	0.029
	1491		0.2500	7.39	3692	10039	752	9.22	0.170	0.076
	1491		0.2500	6.08	3038	12196	914	11.20	0.115	0.112
	1491		0.2500	4.76	2379	14002	1049	12.86	0.079	0.147

$$\text{Flow Parameter} = \left(\frac{L}{G}\right)\left(\frac{\rho_g}{\rho_l}\right)^{.5}$$

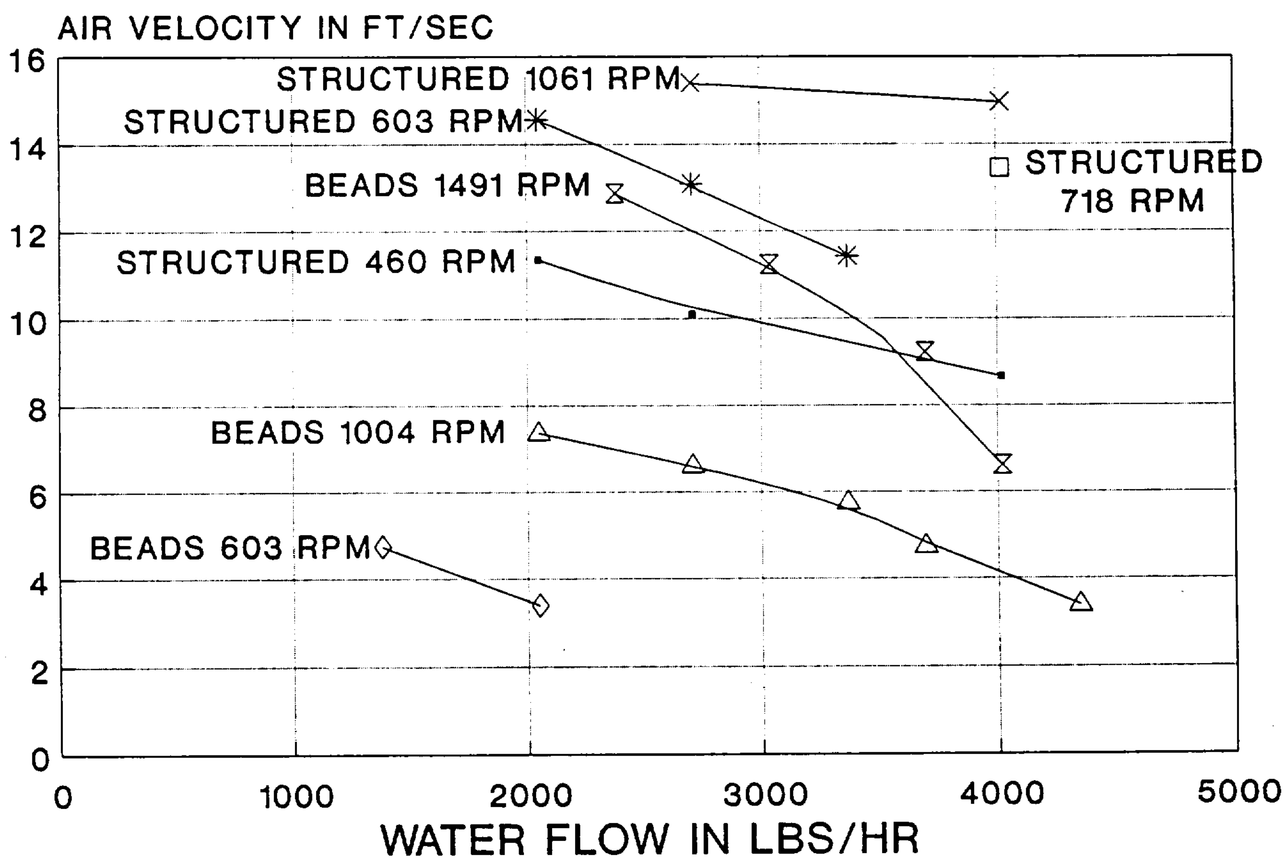


FIGURE 17
FLOODING COMPARISON OF PACKINGS
TEST RESULTS

The effect of the spray angle and the packing ID entrance angle is critical to the flooding performance of the structured packing in a rotating column. The testing, although preliminary, had shown this effect. The structured packing was fabricated to meet the ID at ~90° to allow clear entrance of the water into the passages. The water was injected at ~ 90° to the ID or directly into the structured packing passages when the rotor was at rest. Due to fit-up problems of the structured packing into the rotor the packing had to be trimmed back from 5.5" to 6" ID. This changed the packing entrance angle from near 90° to 45°. Testing at this packing entrance angle and a 90° spray angle produced very high Sherwood flow parameters at 45°, 603 and 718 RPM, Figure 18, and no difference in flooding between clockwise and counterclockwise rotation was observed.

During testing the packing ID was damaged and had to be cut back from 6" ID to 6.5" ID. This caused the entrance of the packing to meet the ID at an angle of ~ 46°. The spray nozzle was also changed in order that the nozzle could be moved closer to the packing ID and the spray angle was set at 30°. This resulted in a decrease in the flooding performance at the same RPM and a large difference in flooding depending on whether the rotation was clockwise or counterclockwise. This is shown by the 718 RPM points, Figure 18.

The importance of the spray angle at higher RPM is shown by the very low 1061 RPM points, Figure 18. The injection angle or tangential velocity of the water jet was not varied during the tests. As the RPM is increased the jet tangential velocity should also be increased in order to allow the water to smoothly enter the packing channel. Not optimizing the jet angle or tangential velocity is thought to have resulted in the low Sherwood number or early flooding.

The data obtained to date has shown the performance improvement which can be obtained with structured packing over

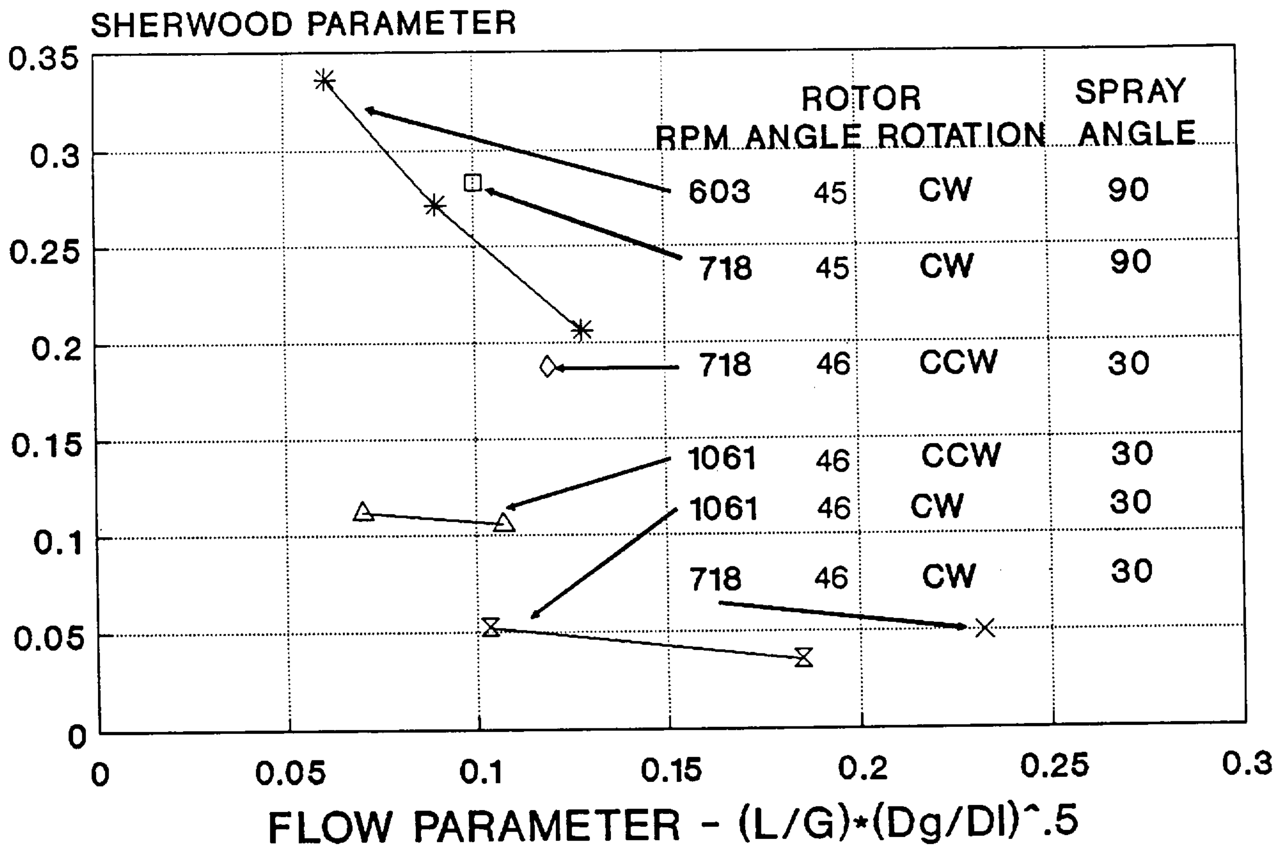


FIGURE 18
STRUCTURED PACKING FLOODING DATA
EFFECT OF LIQUID JET AND PACKING ANGLE

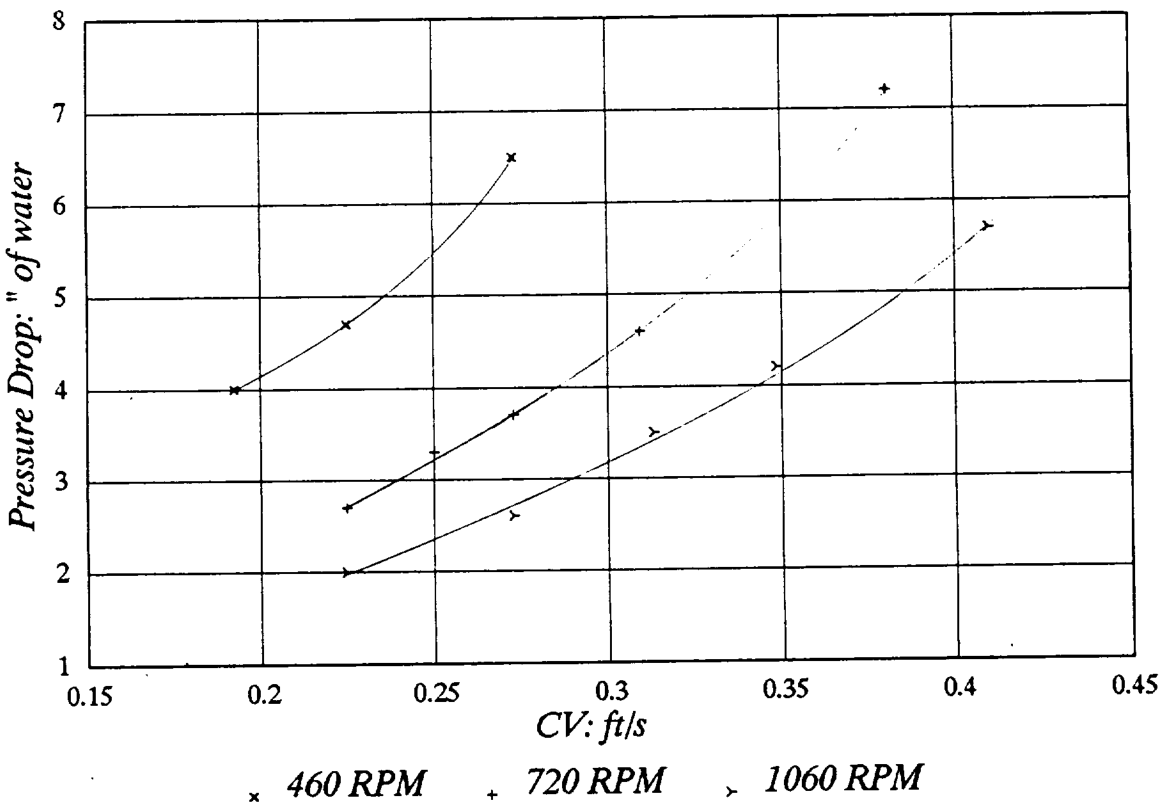
trays and bead packing using a fixed injection angle. By optimizing the liquid injection angle and packing ID starting angle further increases in the structured packing capacity are expected.

Figures 19 to 24 show the air pressure drop through the packing for a constant water flow rate. All of the plots show a lower pressure drop at higher RPM which is due to the higher gravitational field resulting in smoother liquid film.

VII. PERFORMANCE ESTIMATE AT CRYOGENIC CONDITIONS

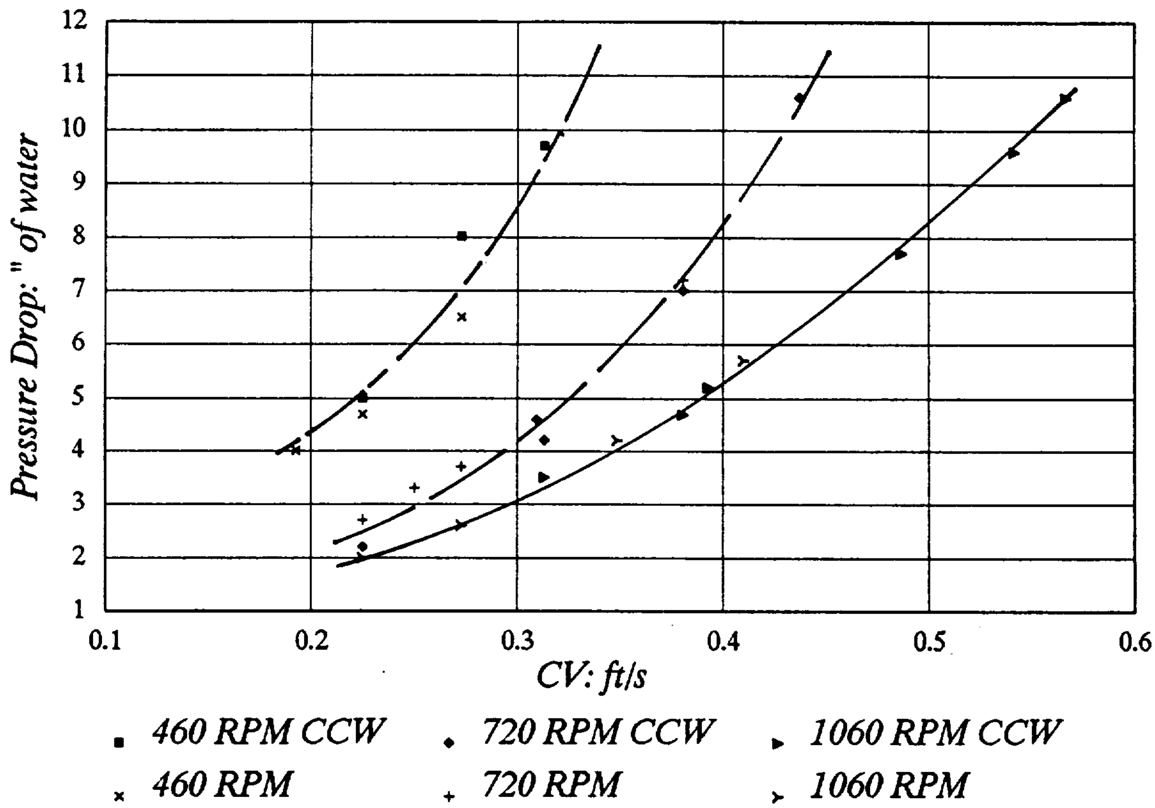
Using the Sherwood parameter for flooding conditions, the capacities of the dumped and structured packings were calculated at cryogenic temperatures for area densities of 360, 700 and 1000 ft^2/ft^3. Their flow capacities in terms of gas velocity (ft/sec) are shown in Table VII. These flow capacities in terms of gas velocity (ft/sec) and reflux ratio, L/G #/# were plotted in Figures 25 and 26 for the dumped and structured packings respectively. Figure 25 shows that the dumped packing will allow gas velocities in the range of 2-4 ft/sec for the low pressure column and in the range of 1-2 ft/sec for the high pressure column. Thus, they will fall far short of the desired velocity of about 11 ft/sec for the low pressure column and about 3.5 ft/sec for the high pressure column. The structured packing, with much better flow capacities, however, meet the design requirements as shown in Figure 26. For the low pressure column, for L/G of 1.125 and $A_o=1000 ft^2/ft^3$ the desired velocity of 10.5 ft/sec is about 6% lower than the experimental value of 11.2 ft/sec. For the high pressure column, the performance of the structured packing at $A_o = 1000\ ft^2/ft^3$ is 8% above the goal of 3.5 ft/sec at L/G of 0.5.

It should be noted that the high area density, of 1000 ft^2/ft^3 has been chosen for the structured packing in order to keep the packing height, (i.e. HETP) low to achieve compactness and light weight, Figure 10. In the final tradeoff, the HETP could be traded off against the flow cross section to obtain an overall optimized



Water Rate: 8 gpm, Air velocity calculated at inner hub
Packed Rotor: 2.25" thk, 3.25" ir, 7" or

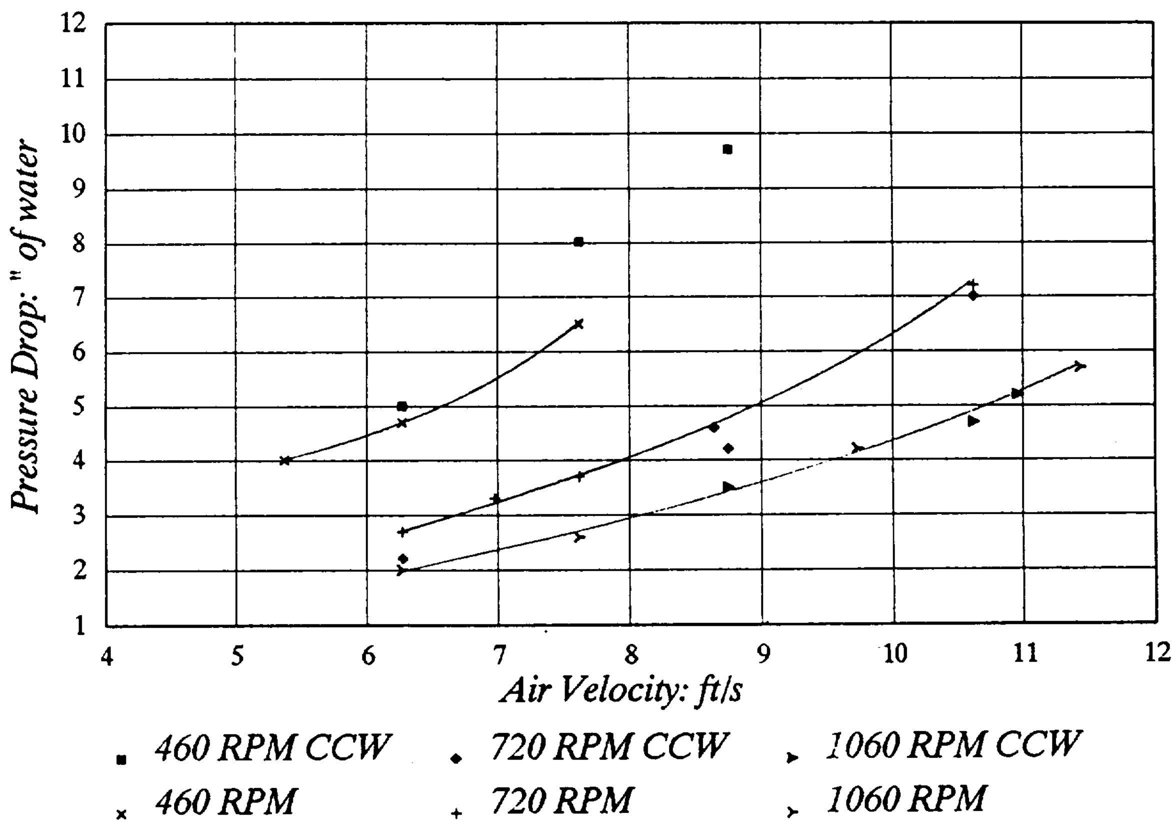
FIGURE 19
RAWC - LINDE STRUCTURED PACKING
PRESSURE DROP VS AIR VELOCITY
AT CONSTANT WATER RATE



Water Rate: 8 gpm, Air velocity calculated at inner hub
Packed Rotor: 2.25" thk, 3.25" ir, 7" or

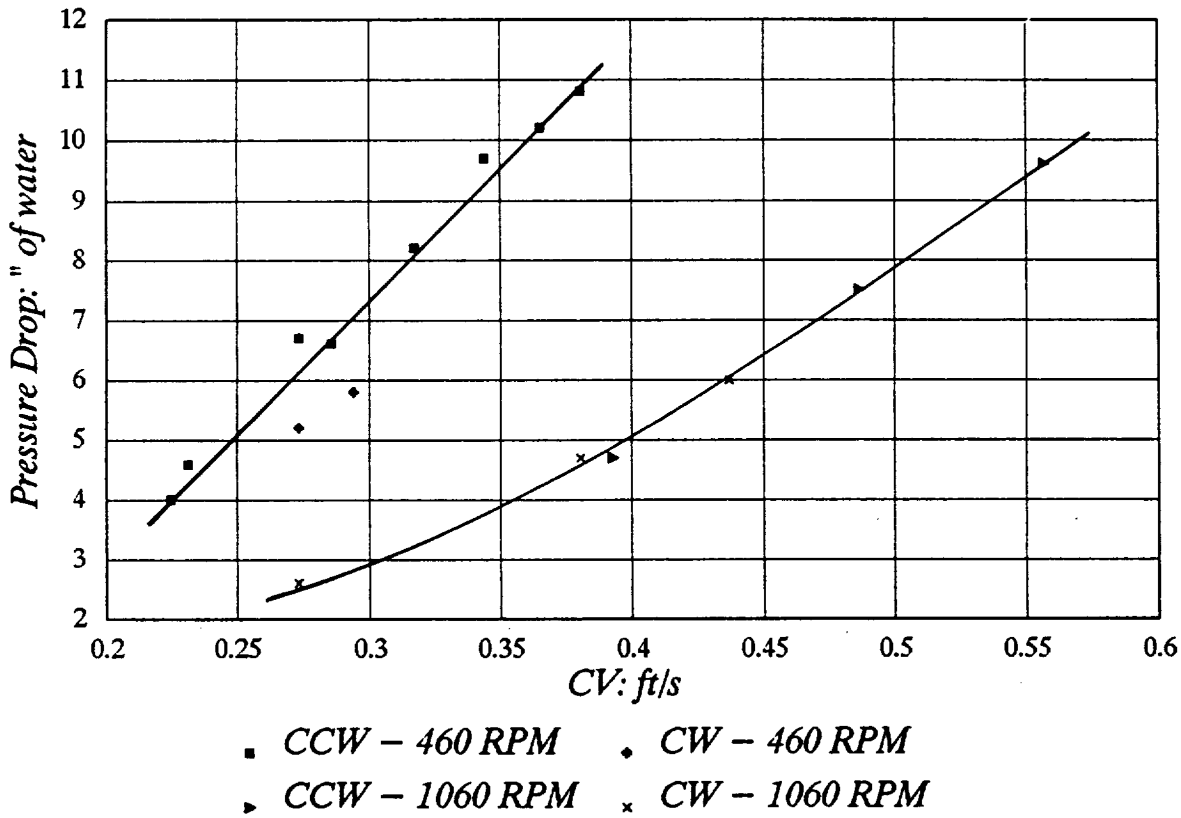
FIGURE 20

**RAWC - LINDE STRUCTURED PACKING
PRESSURE DROP VS AIR VELOCITY
AT CONSTANT WATER VELOCITY**



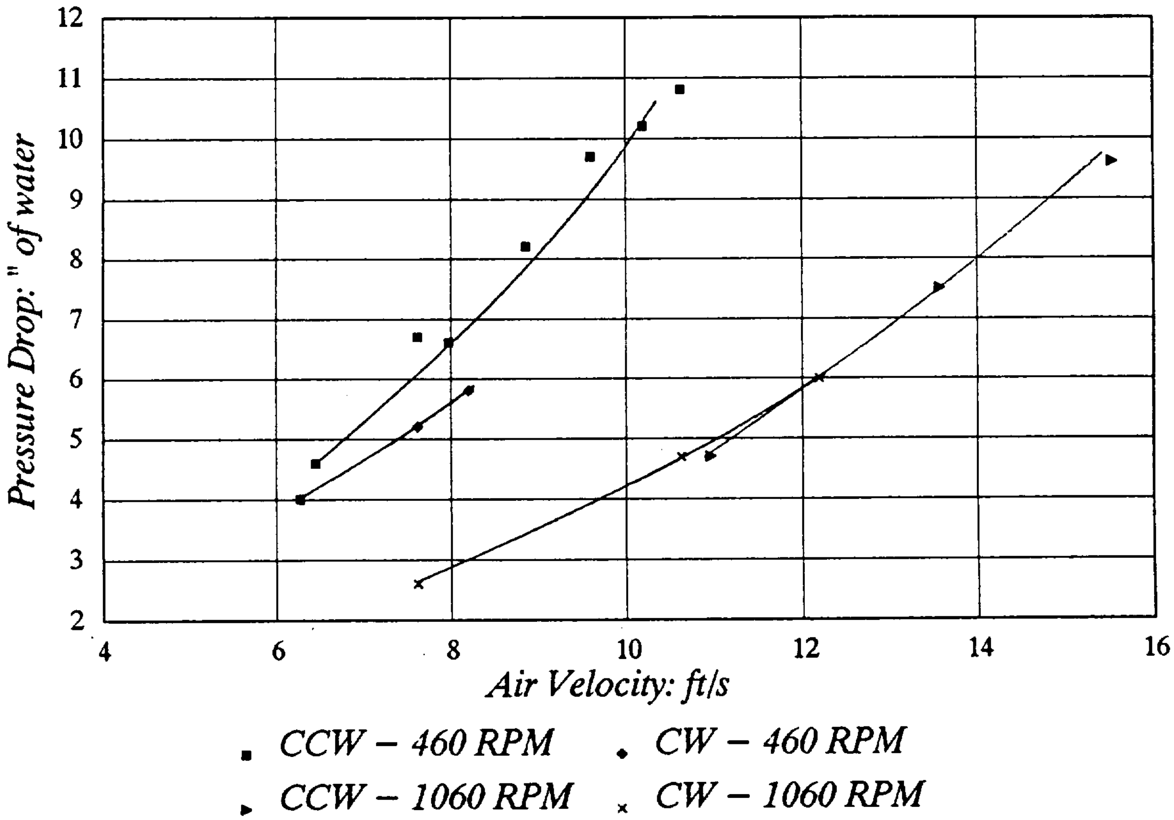
Water Rate: 8 gpm, Air velocity calculated at inner hub
Packed Rotor: 2.25" thk, 3.25" ir, 7" or

FIGURE 21
RAWC - LINDE STRUCTURED PACKING
PRESSURE DROP VS AIR VELOCITY
AT CONSTANT WATER RATE



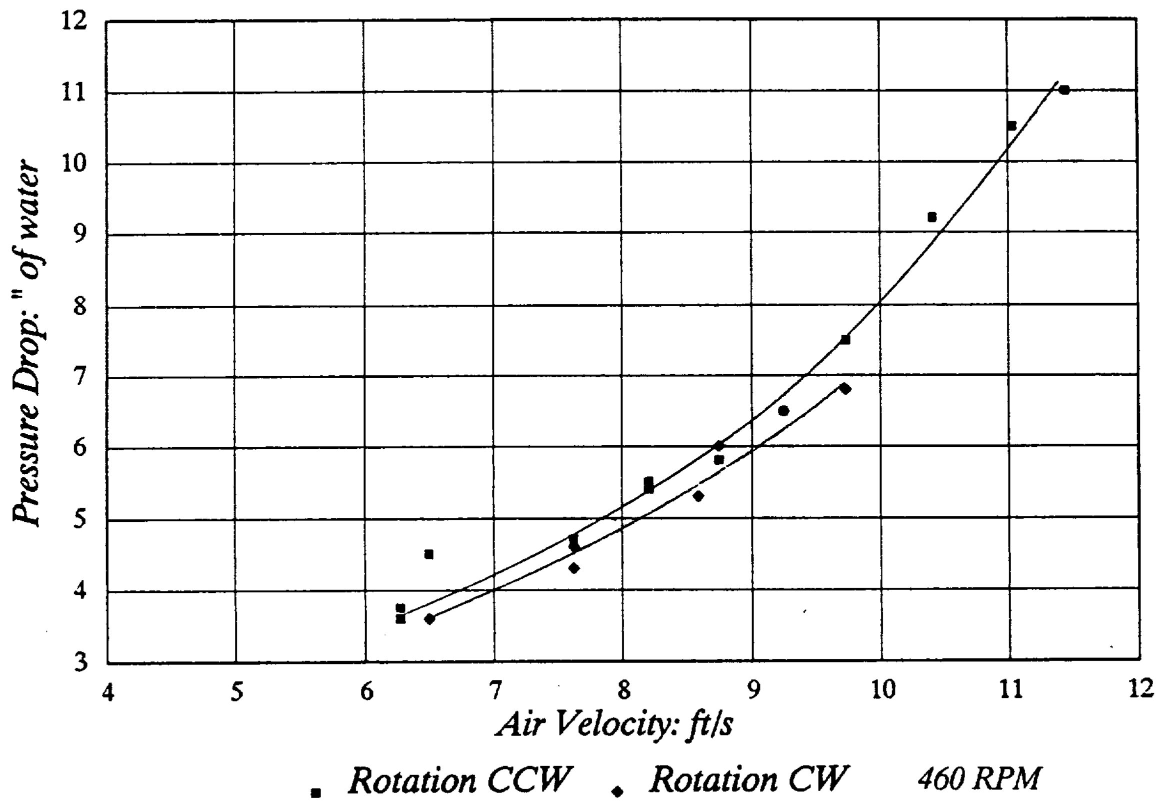
Water Rate: 5.4 gpm, Air velocity calculated at inner hub
Packed Rotor: 2.25" thk, 3.25" ir, 7" or

FIGURE 22
RAWC - LINDE STRUCTURED PACKING
PRESSURE DROP VS AIR VELOCITY
AT CONSTANT WATER RATE



Water Rate: 5.4 gpm, Air velocity calculated at inner hub
Packed Rotor: 2.25" thk, 3.25" ir, 7" or

FIGURE 23
RAWC - LINDE STRUCTURED PACKING
PRESSURE DROP VS AIR VELOCITY
AT CONSTANT WATER RATE



Water Rate: 4 gpm, Air velocity calculated at inner hub
Packed Rotor: 2.25" thk, 3.25" ir, 7" or

FIGURE 24
RAWC - LINDE STRUCTURED PACKING
PRESSURE DROP VS AIR VELOCITY
AT CONSTANT WATER RATE

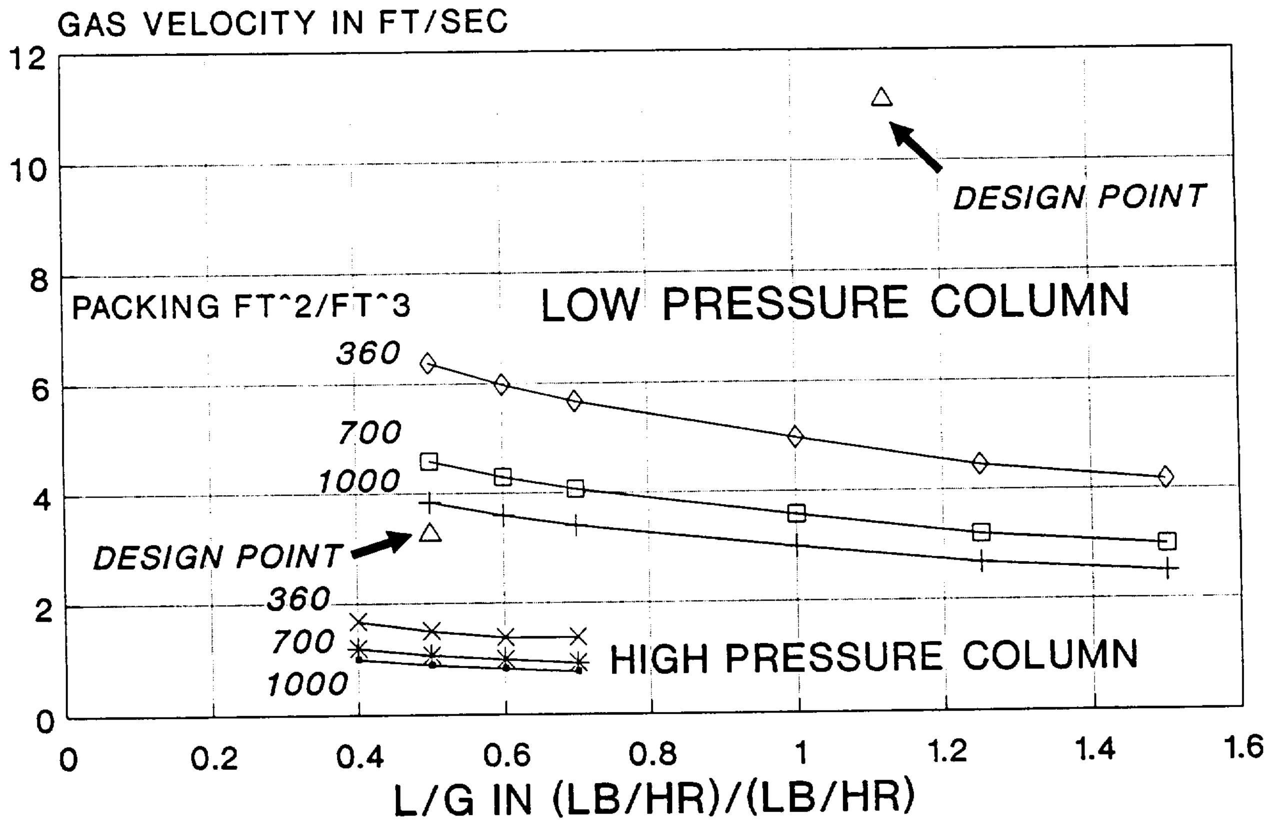


FIGURE 25
BEAD PACKING FLOODING PREDICTION
ROTARY COLUMN CRYO PLANT

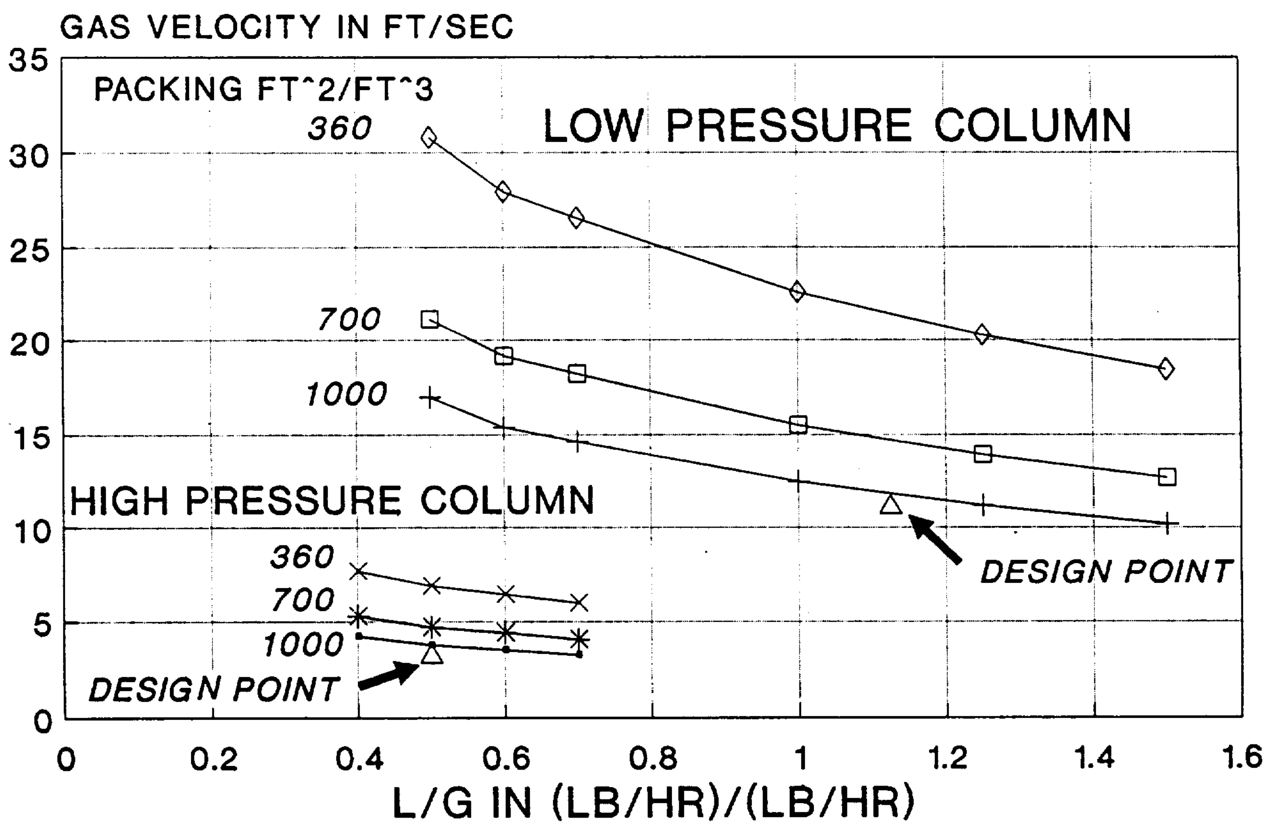


FIGURE 26
STRUCTURED PACKING FLOODING PREDICTION
ROTARY COLUMN CRYO PLANT

Table VII

Gas Flow Capacity of Structured and Bead Packing for Cryogenic Air Separation

Note: Structured Packing has ~4 to 5 times the through put of the bead packing.

Column Type	L/G	Flow Parameter L/G x P vap/P Liq	Sherwood Number	Flooding gas Velocity		
				A = 1000	A = 700	A = 360
				E = .917	E = .942	E = .97
Structured Packing High Pressure	.4	.132	.2	4.23	5.27	7.68
	.5	.165	.16	3.79	4.71	6.87
	.6	.198	.14	3.54	4.41	6.42
	.7	.231	.12	3.28	4.08	5.95
Bead Packing High Pressure				E = .43	E = .43	E = .43
	.4	.132	.11	1.01	1.21	1.68
	.5	.165	.088	.90	1.08	1.50
	.6	.198	.075	.83	1.00	1.39
	.7	.231	.065	.78	.93	1.29
Structured Packing Low Pressure				E = .917	E = .942	E = .97
	.5	.073	.335	17.0	21.1	30.8
	.7	.103	.248	14.6	18.2	26.5
	1.0	.147	.18	12.5	15.5	22.6
	1.25	.184	.145	11.2	13.9	20.3
	1.5	.220	.12	10.2	12.7	18.4
Bend Packing Low Pressure				E = .43	E = .43	E = .43
	.5	.073	.165	3.83	4.58	6.38
	.7	.103	.13	3.40	4.06	5.66
	1.0	.147	.1	2.98	3.56	4.97
	1.25	.184	.08	2.67	3.19	4.44
	1.5	.220	.07	2.49	2.98	4.16

Column Parameters at Inner Radius

	Low Pressure	High Pressure
Inner Radius - ft	.432	2.0
Rotation - Rad/S	60	60
Pressure - psia	56	225
Liquid Viscosity - CP	.111	.060
Liquid Density - lb/ft^3	46.3	38.4
Gas Density lb/ft^3	1.00	4.18
Saturation Temp °K	90.8	111

separator system with respect to weight, volume, mechanical simplicity, pressure drop, windage losses and range of air collection Mach numbers.

VIII. APPLICATIONS

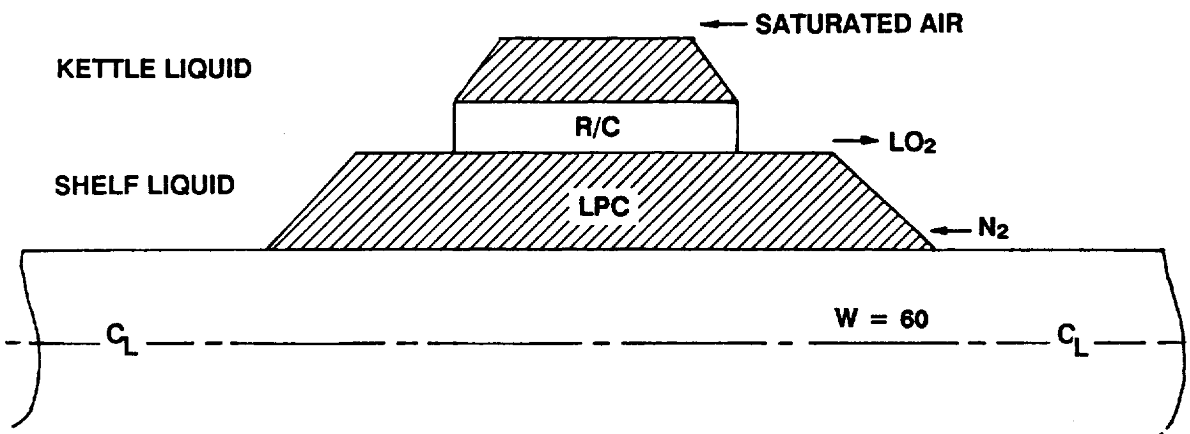
Work in 1960's had indicated that the concept of compact rotating air separators was feasible. This was based on use of sieve trays in the rotating distillation column with weight and volume as indicated in Figure 9(a). Subsequent studies in 1987-88 concluded that the key technology to benefit the future earth to orbit hypersonic plane will be the structured packing to be used in the rotating distillation column, Figure 9(b). Recent experimental study at Linde with structured packing using air/water fluid combination has reinforced the prediction made earlier about the significant improvement in volume and weight possible with the use of suitable packing. Nearly three fold improvements in capacity of the structured packing over that of the random packing was observed in the tests, Table V. Using the Sherwood correlation for predicting the allowable gas velocities at the cryogenic conditions, the superficial velocities of 11.1 ft/sec for the low pressure column and 3.26 ft/sec for the high pressure column were used in designing the advanced rotating distillation column. Mass transfer characteristics of the packing was extrapolated based on available data with an HETP of 1.0" for the packing area density of 1000 ft^2/ft^3, Figure 10. Based on the above information, a much more compact rotating distillation column is envisioned as shown in Figure 9(b). With significant reduction in the flow cross section as well as the radial height of the column, coupled with improved performance predicted for the reboiler/condenser due to its larger radius and higher rotational speed, the distillation column could be arranged in series rather than the earlier version with side-by-side arrangement. The above series arrangement, not only leads to more compact configuration but also greatly simplifies the flow logistics and piping arrangements and leads to a lighter weight system. The above system, it should be noted, is designed for production of 90% liquid oxygen, Figure 27.

Another potential use of a distillation separator is with some recent propulsion concepts for single stage to orbit aircraft which uses a LACE for low speed propulsion, scamjets for intermediate to high speed propulsion and a rocket for the final acceleration to orbital speed. The oxidizer for the rocket is provided by collecting liquid air during the low to medium speed propulsion phase. By inserting a simple single stage enriching column into the system as shown in Figure 28, the oxygen concentration in the collected liquid can be increased to 47%, thus reducing the amount of liquid required and improving the specific impulse of the rocket engine. With the scheme presented, the system modifications are minimal and since existing heat exchangers condense nitrogen reflux liquid, only a rotating distillation section is required. For air flow of 100 lb/sec, the device would have dimensions and characteristics as shown in Figure 28, a flow path as shown in Figure 29, and column flow conditions as given in Figure 30. The process flow schemaic is shown in Figure 31.

IX. CONCLUSIONS AND RECOMMENDATIONS

The air water testing has given reasonable confidence to the throughput and pressure drop of the rotating cryo-column. The mass transfer results are based on extrapolation of data from low area density (200 ft^2/ft^3) structured packing at 1 g to ~ 1000 ft^2/ft^3 and 7 g's. These extrapolations must be verified through experimental cryogenic testing.

In view of the pivotal role of the structured packing for the rotating distillation column and with the encouraging results obtained using the air/water fluid combination, it is recommended that the effort be concerted to determine the mass transfer characteristics (HEPT) of the packings. Furthermore, the



<u>HIGH PRESSURE COLUMN, HPC IN</u> - 2,000 LBS/SEC

I.R 52": L = 60, AREA = 144 FT^2, Ng ~485

O.R. 66": ρ_g = 4.26, Vg = 3.26 FT/SEC

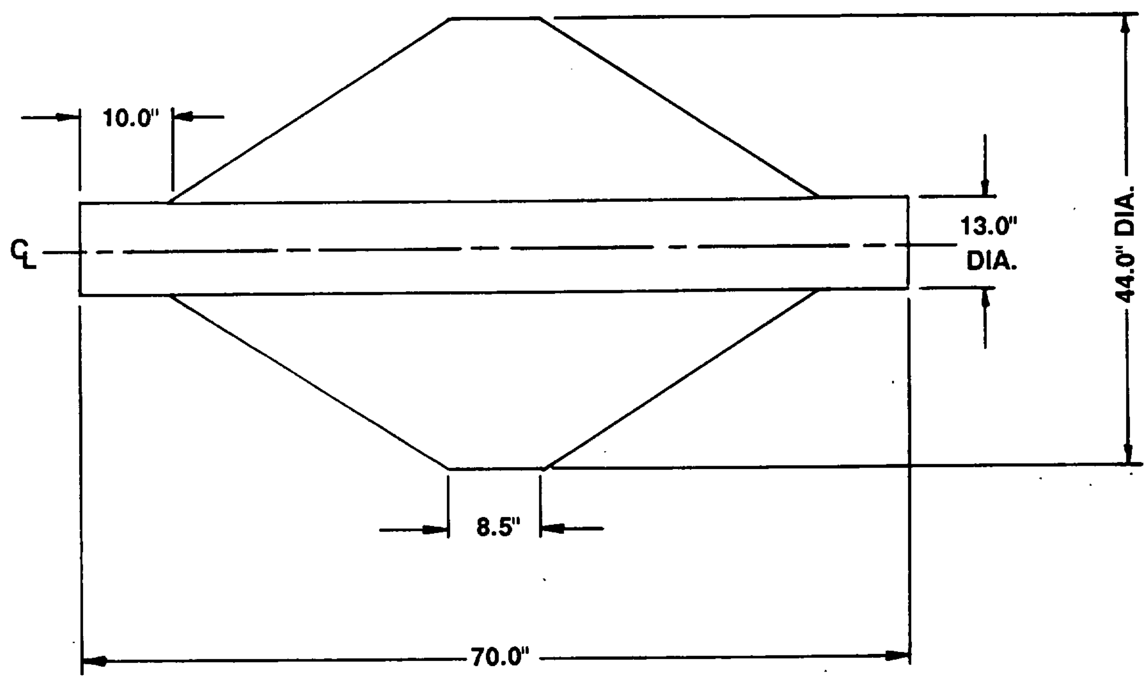
<u>REBOILER CONDENSER, R/C</u>

<u>LOW PRESSURE COLUMN, LPC</u>

I.R. 20": L = 140", AREA = 144 FT^2, Ng - 185

O.R 42" ρ_g = 1.0 Vg = 11.1 FT/SEC

FIGURE 27
ROTATING CRYO COLUMN



FLOW:	100 LB/SEC
RPM:	860
WEIGHT:	450 LBS
POWER:	150 HP
UNITS REG:	2

FIGURE 28
SINGLE COLUMN ROTARY AIR SEPARATOR

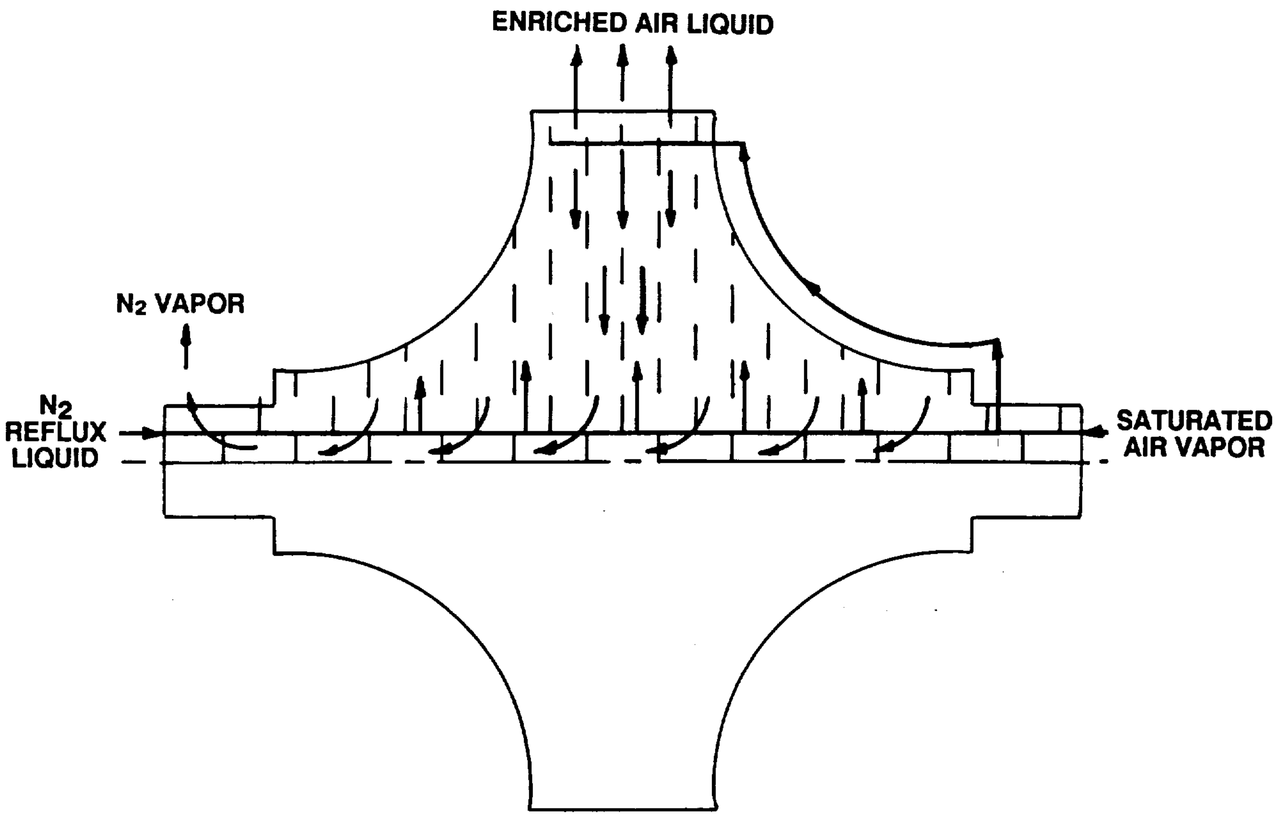


FIGURE 29
SINGLE COLUMN ROTARY AIR SEPARATOR

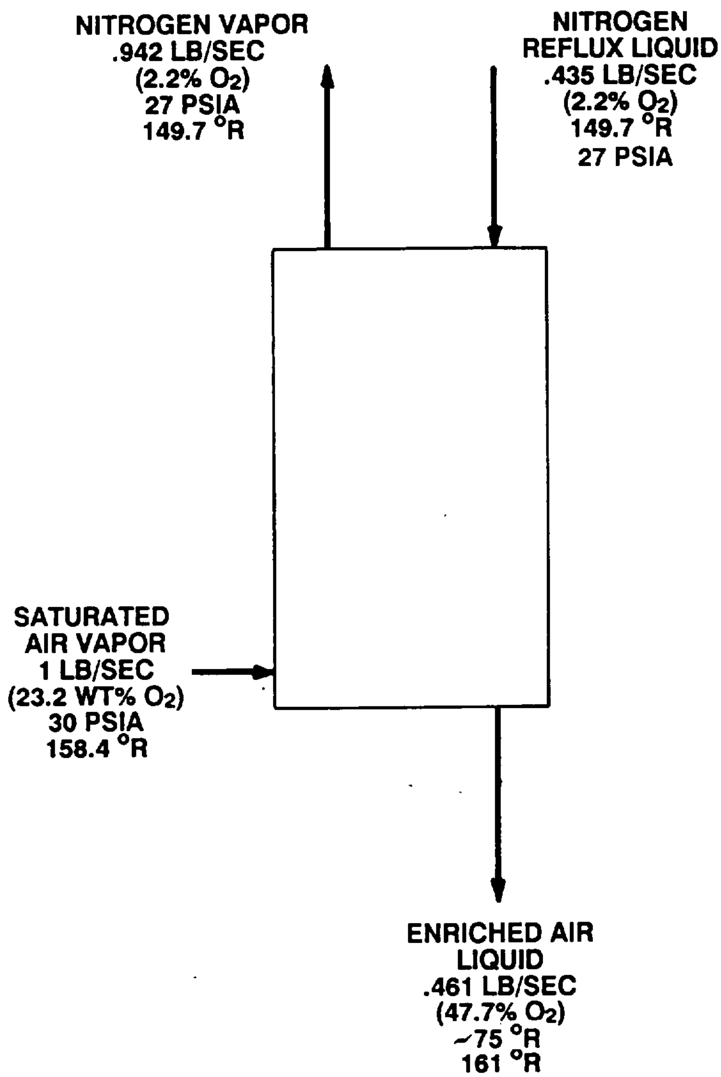


FIGURE 30
FLOW CONDITIONS: SINGLE COLUMN
ROTARY AIR SEPARATOR

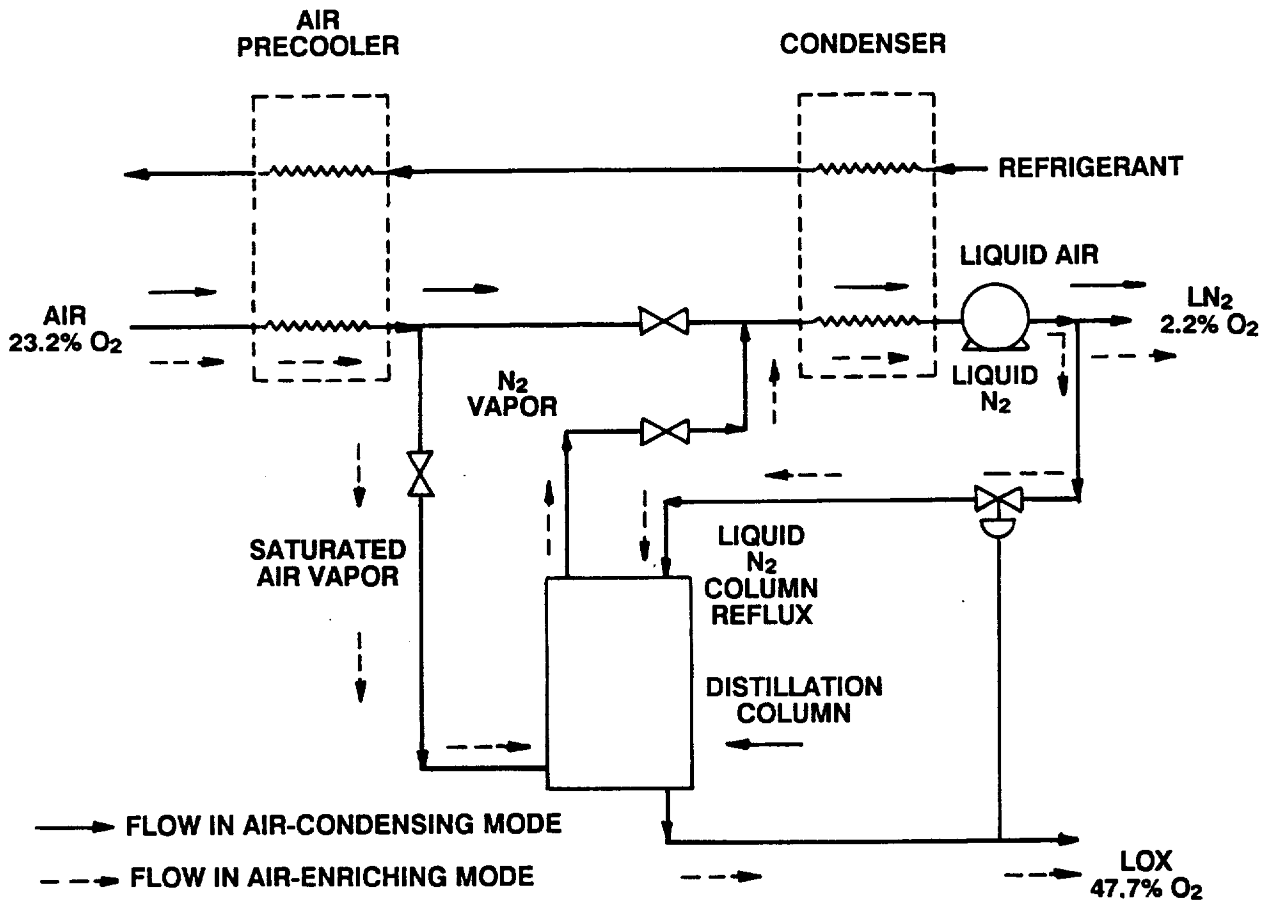


FIGURE 31
DUAL MODE: LIQUID AIR/ENRICHED LIQUID AIR CONDENSING SYSTEM

performance of the structured packing in terms of both the flow capacity and the HETP be determined under actual cryogenic conditions. UCIG's Linde Division offers its established fixed cryogenic distillation test facility with suitable streams generated and instrumentation to evaluate packings at cryo temperatures, Figure 32. A rotating column would be integrated into the existing facility as shown in Figure 33.

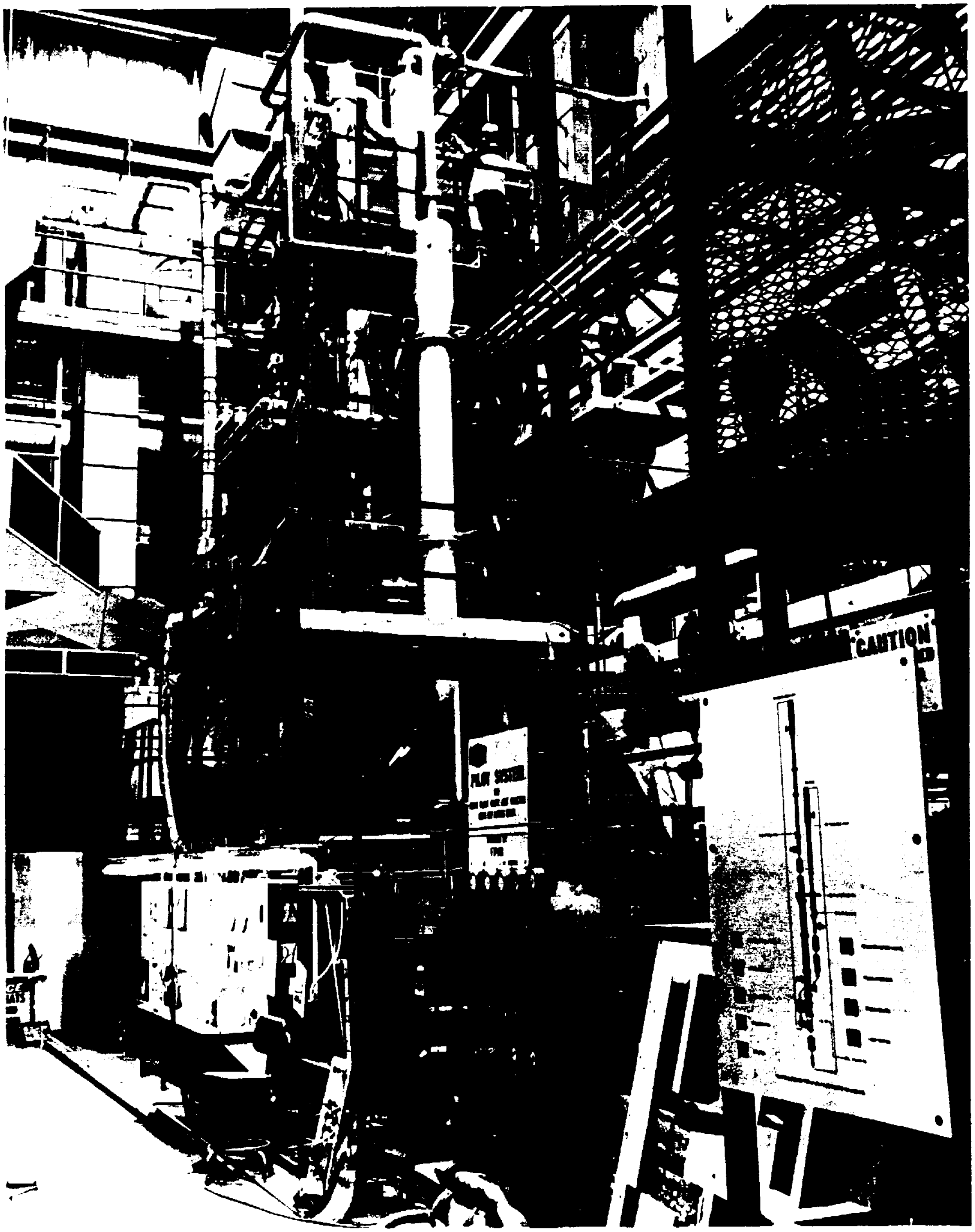


FIGURE 32
LINDE DISTILLATION TEST FACILITY

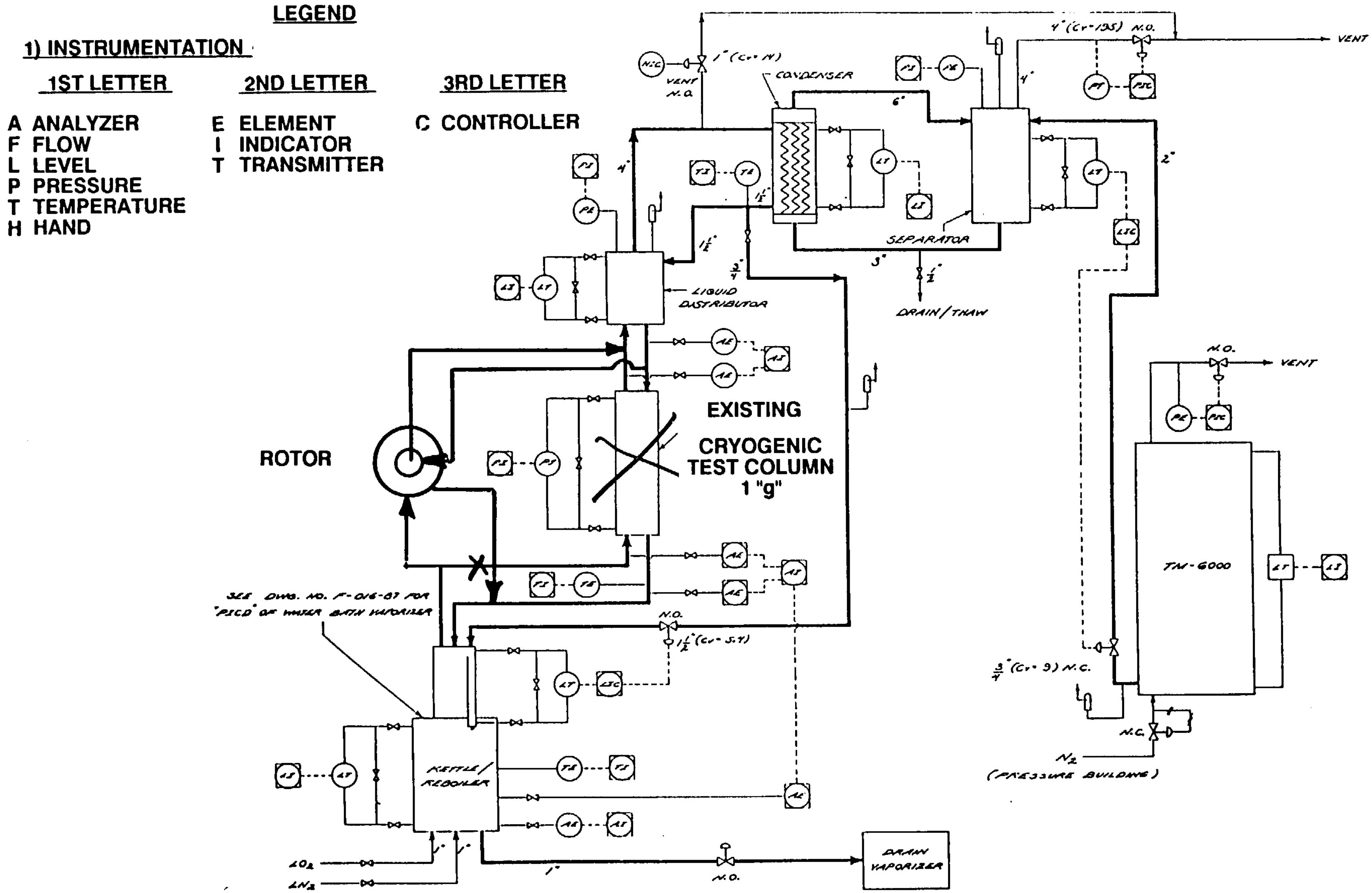


FIGURE 33
ROTATING CRYOGENIC DISTILLATION TEST FACILITY

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13. ABSTRACT ***(Maximum 200 words)***

Several air breathing propulsion concepts for future earth-to-orbit transport vehicles utilize air collection and enrichment, and subsequent storage of liquid oxygen for later use in the vehicle mission. Work performed during the 1960's established the feasibility of substantially reducing weight and volume of a distillation type air separator system by operating the distillation elements in high "g" fields obtained by rotating the separator assembly. This contract studied the capacity test and hydraulic behavior of a novel structured or ordered distillation packing in a rotating device using air and water. Pressure drop and flood points were measured for different air and water flow rates in gravitational fields of up to 700 g. Behavior of the packing follows the correlations previously derived from tests at normal gravity. The novel ordered packing can take the place of trays in a rotating air separation column with the promise of substantial reduction in pressure drop, volume, and system weight. The results obtained in the program are used to predict design and performance of rotary separators for air collection and enrichment systems of interest for past and present concepts of air breathing propulsion (single or two-stage to orbit) systems.

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